Energy, Mines and Resources Canada | Energie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

EFFECT OF SEVERAL RADIATION CONTROL MEASURES FOR REMEDIAL PURPOSES IN A DWELLING IN THE ELLIOT LAKE AREA

J. BIGU

ELLIOT LAKE LABORATORY

MAY 1986

This document is an interim report prepared for discussion and review purposes only and represents neither the opinion of the Department of Energy, Mines and Resources (CANMET)

Ce document est un rapport préliminaire préparé et rédigé pour discussion et révision en fin de publication et de documentation seulement et ne représente nullement l'opinion définitive de l'Energie, Mines et Ressources Canada, Centre canadien de la technologie des minéraux et de l'énergie (CANMET)

66 pp

MINERAL AND ENERGY TECHNOLOGY
MINING RESEARCH LABORATORIES
DIVISION REPORT M&ET/MRL 86-66(TR)

MICROMEDIA

EFFECT OF SEVERAL RADIATION CONTROL MEASURES FOR REMEDIAL PURPOSES IN A DWELLING IN THE ELLIOT LAKE AREA

by

J. Bigu*

ABSTRACT

A monitoring program was undertaken to measure radiation levels (radon gas and radon daughter concentration levels) in a dwelling in the Elliot Lake area. Several radiation control systems were implemented in the house for compliance purposes. The effect of ventilation, an electronic air cleaner (installed in the air ventilation system), air mixing fans, and ion-generators on the radiation level was investigated for a period of two weeks, during which one or more of the above control systems was operated. In addition to radioactivity measurements, other variables were also measured such as aerosol concentration and unattached radon daughter fraction. Meteorological data inside and outside the dwelling were also collected. These included indoor and outdoor temperature, indoor relative humidity, barometric pressure, outdoor dew point, and wind speed. The outdoor temperature had quite a significant inverse effect on radiation levels. The most effective control system was ventilation, followed by the air cleaner. Only ventilation was effective in reducing radon concentration levels. It is suggested that more studies over longer periods should be conducted to better assess the effectiveness of the above control systems.

---

*Research Scientist and Radiation/Respirable Dust/Ventilation Project Leader, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario.

DÉTERMINATION DE L'EFFET DE PLUSIEURS MESURES DE CONTRÔLE DU RAYONNEMENT DANS UNE RÉSIDENCE D'ELLIOT LAKE, DANS UN BUT CORRECTIF

par

J. Bigu*

RÉSUMÉ

Un programme de surveillance a été mis sur pied dans le but de mesurer les niveaux de rayonnements (soit les niveaux de concentration du radon et des produits de filiation du radon) dans une résidence d'Elliot Lake. Plusieurs systèmes de contrôle du rayonnement ont été installés afin d'effectuer des mesures du rayonnement en conformité avec la loi. L'effet d'un système de ventilation, d'un filtre à air électronique (installée dans le système de ventilation), des ventilateurs de mélange et des générateurs d'ions sur les niveaux de rayonnements a fait l'objet d'une étude d'une durée de deux semaines pendant lesquelles un ou plusieurs systèmes de contrôle susmentionnés fonctionnaient. En plus des mesures de radioactivité, on a mesuré d'autres variables tel que la concentration d'aérosols et de fractions libres des produits de filiation du radon. Les données météorologiques à l'intérieur et à l'extérieur de la résidence ont été recueillies. Ces données comprenaient, entre autres, les températures à l'intérieur et à l'extérieur de la résidence, l'humidité relative à l'intérieur, la pression barométrique, le point de rosée extérieur et la vitesse du vent. La température extérieure avait un effet inverse important sur les niveaux de rayonnements. Parmi les systèmes de contrôle étudiés, le système de

---

*Chercheur scientifique et Chef de projet Rayonnements/Poussières respirables/Ventilation, Laboratoire d'Elliot Lake, CANMET, Énergie, Mines et Ressources Canada, Elliot Lake (Ontario).

ventilation s'est révélé le plus efficace suivi du filtre à air. Toutefois, seulement le système de ventilation s'est avéré efficace pour réduire les niveaux de concentration du radon. Il est proposé d'effectuer d'autres études couvrant des périodes de temps plus longues, dans le but d'évaluer l'efficacité des systèmes de contrôle susmentionnés.

CONTENTS

	Page
ABSTRACT	i
RESUME	iii
INTRODUCTION	1
THEORETICAL BACKGROUND	2
EXPERIMENTAL PROCEDURE AND METHODS	4
EXPERIMENTAL RESULTS AND DISCUSSION	8
CONCLUSIONS AND REMARKS	20
ACKNOWLEDGEMENTS	23
REFERENCES	23

TABLES

No.		
1.	Test schedule during implementation of the different radiation control systems program	26
2.	Radiation data collected before the implementation of the different radiation control systems program	27
3.	Data for several variables before the implementation of the different radiation control systems program	28
4.	Maximum, minimum and mean values for several variables measured by grab-sampling before the implementation of the different radiation control systems program	29
5.	Maximum, minimum and mean values for several variables measured by grab-sampling during the implementation of the different radiation control systems program	30

FIGURES

1.	Radon gas concentration as determined by several methods, techniques, and instrumentation. Data represent average values obtained before the radiation control systems program	31
2.	Radon daughter Working Levels as determined by several methods, techniques and instrumentation. Data represent average values obtained before the radiation control systems program	32
3.	Radon gas concentration, radon daughter Working Level, and ventilation rate versus time	33
4.	Working Level ratio, unattached fraction, and aerosol concentration versus time	34
5.	Radon progeny concentration versus time	35

No.		Page
6.	Disequilibrium ratio versus time	36
7.	Radon daughter Working Level versus time. Also shown are the outdoors temperature and pressure. Data taken in the living room	37
8.	Radon daughter Working Level versus time. Also shown are the outdoors temperature and pressure. Data taken in the living room	38
9.	Radon daughter Working Level versus time. Also shown are the outdoors temperature and pressure. Data taken in the living room	39
10.	Radon daughter Working Level versus time. Also shown are the outdoors temperature and pressure. Data taken in the living room	40
11.	Radon daughter Working Level versus time. Also shown are the outdoors temperature and pressure. Data taken in the living room	41
12.	Radon gas concentration, and radon daughter Working Level versus time. Also shown are the outdoor temperature, pressure and control operations. Data taken in the living room, and in the laundry room	42
13.	Radon gas concentration versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the laundry room	43
14.	Radon gas concentration versus time. Also shown are the outdoors temperature, pressure, and control operations	44
15.	Radon gas concentration versus time. Also shown are the outdoors temperature, pressure, and control operations	45
16.	Radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations in living room and laundry room	46
17.	Radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, aerosol concentration, and control operations. Data taken in the living room	47
18.	Radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, aerosol concentration, and control operations. Data taken in the laundry room	48
19.	Radon gas concentration versus time. Also shown are the outdoors temperature, pressure, aerosol concentration, and control operations. Data taken in the living room	49
20.	Radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, aerosol concentration, and control operations. Data taken in the living room	50
21.	Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the laundry room	51

No.		Page
22.	Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the living room	52
23.	Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the laundry room.....	53
24.	Radon gas concentration and radon daughter Working Level versus control operations. Data taken in the living room	54
25.	Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the livong room	55
26.	Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature, pressure, and control operations. Data taken in the laundry room	56
27.	Radon gas concentration and radon daughter Working Level versus time	57
28.	Radon gas concentration and radon daughter Working Level versus time	58
29.	Radon gas concentration versus time	59
30.	Radon daughter Working Level versus time	60

INTRODUCTION

Some building materials contain appreciable amounts of ^{226}Ra. Furthermore, ^{238}U is distributed more or less uniformly in the earth's crust, and hence, is found in soil materials. Through a series of radioactive decays, ^{238}U decays into ^{226}Ra, which in turn decays into the relatively inert radioactive gas radon (^{222}Rn). Hence, building materials and soil are sources of ^{222}Rn.

Radon readily diffuses through building materials and soil finding its way into living spaces of dwellings and commercial and industrial buildings. Radon readily decays into its short-lived decay products, i.e., radon daughters.

Because radon daughters pose a potential health hazard when inhaled, monitoring of radon and radon daughter levels is important. When excessive levels of radiation are found in living atmospheres, remedial action measures are necessary in order to reduce radon and radon daughter concentrations to acceptable levels.

Unacceptable levels of radon and radon daughters have been found in some houses in several communities across Canada, the U.S.A., Europe and other parts of the world. By law, immediate remedial action must be taken as soon as such a situation is identified in order to prevent undue radiation exposure to dwellers in particular, and the general population at large.

Some dwellings in the town of Elliot Lake (Ontario) exhibited higher than acceptable concentration levels of radon and radon daughters. Remedial action was taken after this anomalous situation was identified. Shortly after remedial action was taken, a new series of radioactivity measurements was carried out to ensure that radiation levels were within acceptable limits.

In one specific case, a house was chosen for a detailed pilot study in

order to investigate the effectiveness of a number of remedial measures implemented in the house. The work was conducted with the consent of the dwellers. It was requested by Atomic Energy of Canada Limited (AECL), which requested the assistance of the Elliot Lake Laboratory (CANMET) in carrying out experimentation and analyzing data collected in these studies.

Several organizations provided AECL with additional radiation instrumentation for these studies. These included: Atomic Energy Control Board (AECB), the Ontario Ministry of Labour (MOL), National Health and Welfare (NHW), and CANMET. In addition, DMSA (Toronto), a consulting firm, was contracted to carry out experimental work.

THEORETICAL BACKGROUND

There are a number of factors that can affect the concentration of radon and its decay products in an enclosed, or partially enclosed, environment.

The radon gas concentration in an enclosed, or partially enclosed, environment depends on:

1. The radon exhalation rates from building materials, and the soil (ground) on which the house is built. Furthermore, the exhalation rate is affected by the temperature and moisture content of ^{226}Ra-bearing building materials and soil. Barometric pressure has a pronounced inverse effect on the radon exhalation rate by convective transport mechanisms. Physical and geometrical considerations also influence the radon gas level and its distribution in the house.
2. Air exchange rate in the house. This may be by natural means, e.g., drafts or currents created by wind and by temperature differentials between inside and outside the house through 'leaks' in the walls, foundation, and roof, or by forced air exchange by a ventilation system.

and/or an air conditioning system. In addition, electrical, wood-burning, gas and oil heating systems differ significantly from each other, and hence, their air exchange characteristics in dwellings are quite different. The effect of opening and closing doors and windows is, of course, quite significant.

3. Type of drainage system for removing wastes from the house, and collecting water from the soil around the house by, say, a weeping tile system, into the main drainage system. For instance ^{222}Rn in the soil can dissolve in rain water entering the basement of a dwelling through the weeping tile system.
4. Kind of building materials and soil physical characteristics. Elevated radiation levels have been measured, as expected, in houses partially built with radioactive backfill material, e.g., basements and driveways. The emanation characteristics of materials depend, in addition to their ^{226}Ra content, on their porosity and permeability. Houses built on rocky or sandy substrata exhibit quite pronounced differences in radon exhalation rates, as theoretically predicted.

The radon daughter concentrations in an enclosed, or partially enclosed, environment depend on the ^{222}Rn concentration, and hence, also on items 1 to 4 discussed above.

However, the radon daughter concentrations also depend on the aerosol concentration, which determines the ratio of unattached to attached radon daughter fractions, and hence the radon daughter fraction plated-out on large surfaces such as walls, ceiling, floor, furniture, and other large objects. The aerosol concentration, size distribution and type(s) of aerosol are determined by a number of activities in the house such as cooking habits, smoking, the heating system, and other activities.

Theoretical models, for simple geometries, have been published in the

literature to calculate radon and radon daughter concentrations in dwellings. The study presented here was intended only to evaluate the efficiency of several methods to control radiation levels in dwellings. No attempt was made to compare experimental and theoretical data. The reader interested in the theoretical aspects of calculating radiation levels in dwellings should consult the pertinent bibliography (1-3) and references therein.

EXPERIMENTAL PROCEDURE AND METHODS

A house in the town of Elliot Lake was chosen for the tests. The house is a split-level dwelling with concrete block foundation and exposed earth in the crawlspace. Pre-remedial radiation levels averaged 0.12 WL. The exposed earth in the crawlspace was covered, but the radiation level (WL) was not brought down below the remedial action criterion of 0.02 WL.

For the first four weeks, 'background' radiation level measurements, as well as other environmental and meteorological measurements, were carried out prior to introducing any changes in the operation of the radiation control systems installed in the house. This phase of experimentation was followed by two-weeks of measurements conducted during the operation of one or more of the radiation control systems available.

The remedial control systems available in the house were as follows:

1. A ventilation system for varying the indoor/outdoor air exchange rate in the house. This ventilation system was provided with a heat exchanger to minimize energy losses to the outside.
2. An electronic air cleaner in series with the air circulation system. The air cleaner consisted of a fan drawing air through a filter followed by an ionizer to produce electrically-charged airborne particles which were subsequently removed by electrostatic precipitation.
3. In addition to items 1 and 2, fans and air ionizers were installed in the

house. Fans were operated in order to plate-out radon daughters on the fan blades (4-8), and to induce radon daughter plate-out on nearby large surfaces, thereby decreasing the airborne radon daughter concentration. Ionizers were used because it was observed in the course of laboratory work in a radon/thoron test facility (RTTF) that radon and thoron daughter concentrations were reduced quite significantly when an air ionizer was operated (7,8). It should be noted that radon gas levels are not affected by fans or ionizers.

A schedule was designed to allow for testing of individual components of the remedial systems installed in the house. In addition, tests were conducted when none of the above components were in operation and when all components were operated.

A number of variables were determined during experimentation. These included: radon gas concentration, radon daughter concentrations, radon daughter Working Level WL(Rn), sometimes also indicated simply by WL, radon daughter unattached fraction, indoor temperature, indoor relative humidity, condensation nuclei concentration, ion concentration, and ventilation, i.e., air exchange rate. In addition, outdoor dew point, outdoor temperature, barometric pressure and wind speed data were collected from the airport and the Elliot Lake Laboratory.

Radon gas concentrations were determined by grab-sampling using scintillation cells, by continuous monitoring systems such as the AB-5/EL system (9), manufactured by Pylon Electronic Development (Ottawa), and by passive integrating devices such as Terradex (USA) track-etch (Type F) detectors, the National Radiation Protection Bureau (NRPB, U.K.) passive integrating radon detectors, which also use track-etch technology, and by means of PRIMs (passive radon integrating monitors), instruments developed by EDA (Toronto), based on a design by AECL (10).

Radon daughter Working Levels were determined by grab-sampling using the Kusnetz method (11), and a modified Markov, Rolle, and Kusnetz (MMRK) counting scheme (12). The latter method also allowed determination of individual radon daughter concentrations.

Radon daughter Working Levels were also determined by several continuous monitoring systems such as the Pylon AB-5/AEP-47 system (13), manufactured by Pylon, an EDA Working Level continuous monitor model WLM-300, an AlphaNUCLEAR personal dosimetry/environmental monitor model AlphaPRISM, and two integrating Working Level monitors, namely: The Ministry of Labour (MOL) Integrating Working Level Detector (MOL-IWLD), and a modified Working Level monitor model MOD-225, manufactured by EDA.

The radon daughter unattached fraction was estimated by the wire screen method (14-16). Ventilation rates were measured using the sulphur hexafluoride (SF_6) technique. Aerosol concentrations were estimated using a condensation nuclei counter (CNC) manufactured by Environment One (U.S.A.). Indoor temperature and relative humidity were measured using a sling psychrometer and by means of a chart hydrothermograph model 612, manufactured by Honeywell.

Since most of the instrumentation used for measuring radiation levels has been adequately described in the literature, no further details of their mode of operation or characteristics will be given here.

Monitoring instrumentation was installed mainly in two rooms of the house, the laundry room in the basement, and in the main living room on the first floor.

It should be noted that although every attempt was made to design the tests so that the effects of the different remedial action control systems could be thoroughly, and independently, investigated, some practical difficulties beyond our immediate control made analysis of the experimental

data difficult. Thus, the activity and habits of the occupants of the house were not known in detail. The occupants were understandibly reluctant to disclose certain information. Unfortunately, most of this information was important to the analysis of the data.

Little information was available on the cooking and smoking habits of the dwellers. Furthermore, as the experimentation was conducted in early Spring, the frequency and duration regarding opening and closing of windows, and the like, could not be ascertained satisfactorily. Finally, time constraints, and personal consideration on the part of the dwellers, precluded experimentation with remedial action control systems to be extended beyond two weeks.

As indicated previously, the first few weeks of the tests were devoted to studying the effects of meteorological and environmental factors on radiation levels in the house. During the second phase of the tests, the effect of the control systems was investigated as follows. All control systems were turned off on a Friday afternoon, and the radiation level in the house was monitored continuously during the weekend. The next Monday, the control systems were turned on in a sequential order, one each day. In this way, the effect of each control system on the radiation level could be studied independently. By Friday all control systems were operating simultaneously. The systems were maintained on over the weekend, after which they were turned off, starting on Monday, in a sequential but reverse order as compared with the previous week. The test schedule for this phase of the program is shown in Table 1.

The next section presents experimental data from the tests conducted in the house. It should be noted that although calibration of the instrumentation used before and after the tests was carried out at the Elliot Lake Laboratory, the calibration factors obtained have not been used in this

work as only relative changes, and not accurate absolute values are of interest here.

EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 shows the test schedule followed during the implementation of the different radiation control systems program. Tables 2 to 4, and Table 5 show radiation and meteorological data acquired before and during the implementation of the radiation control systems program, respectively. It should be noted that the ventilation system in the house was operating prior to the implementation of other radiation control systems. This was necessary because the dwelling did not meet the radiation level criteria set by AECB, i.e., $\leq$20 mWL, without some remedial action. Because of this, radiation levels during the radiation control systems program may appear on some occasions higher than that during the remedial action program.

Data tabulated in Tables 2 to 4 show that radiation levels, i.e., WL(Rn) and ^{222}Rn concentration, [^{222}Rn], and aerosol concentration (N) were higher in the basement (laundry room) than in the living room (first floor). This is to be expected on theoretical grounds for [Rn-222], and hence WL(Rn), for non-uniformly, unevenly, and inefficiently ventilated areas (see also Figures 1 and 2). It should be noted that square brackets are used in this report to indicate concentration.

Figures 1 and 2 show, respectively, the average WL(Rn) and ^{222}Rn concentration for the laundry room (basement) and the living room. The values in these histograms were obtained using different methods and instrumentation, as indicated in Table 2.

Figures 3 to 6 show some of the grab-sampling data collected during implementation of the radiation control systems program. Figures 3 and 5 show five quite distinguishable periods during which a clear relationship between

the operation, or lack of operation, of some radiation control systems and the radiation levels can be observed.

The periods 850501 to 850503, 850508 to 850510, and 850516 to 850517 are characterized by low radiation levels. During these three periods, either all or a combination of the most effective radiation control systems were operating. The periods 850503 to 850508 and 850511 to 850515 are characterized by high radiation levels. During these two periods, either all or a combination of the radiation control systems were turned off. The effect of the systems can be better visualized on data collected by automated continuous monitoring systems, as shown in Figures 14 to 18 and 21 to 30.

In general, radiation levels, by grab-sampling, were higher in the basement (laundry room) than in the living room (see Figures 3 and 5). This situation is similar to that prior to the implementation of control systems. Again, these differences will become obvious from data collected by continuous monitoring systems.

Figure 6 shows that the ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$:

1. both follow the same pattern for both the living room and the laundry room.
2. as expected, $[^{214}Pb]/[^{218}Po]$ is larger than $[^{214}Bi]/[^{218}Po]$;
3. broadly speaking, the above ratios follow the same approximate pattern as that for WL(Rn), $[^{222}Rn]$, $[^{218}Po]$, $[^{214}Pb]$, and $[^{214}Bi]$.

The two broad maxima for the ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$ shown in Figure 6 can tentatively be ascribed to 'aging' of the air, to selective removal of radon daughters at different rates, or to a combination of both (see Table 1). It is known that the above ratios can be altered by changing the air exchange rate in the house, or by operating an electronic air cleaner (17), a negative ion-generator (7,8), mixing fans (4-8), and by filtration. Furthermore, meteorological conditions such as air moisture

content, aerosol concentration, size distribution and tracer gases can also have an effect on these ratios. Because of the simultaneous operation of several control systems and because meteorological conditions changed significantly during the periods during which maximum and minimum values for the radon daughter ratios occurred, it is difficult to determine the time origin of these changes. It should be noted that the aerosol concentration varied quite markedly, and rapidly, over this period (see Figure 4), due most probably to working and smoking activities in the house, and possibly because of varying atmospheric conditions.

Figure 4 shows that the Working Level Ratio (WLR) varied from 0.1 to over 0.4. The WLR is defined as the ratio $(WL(Rn)/[^{222}Rn])x10^{2}$ where, $[^{222}Rn]$ is given in $pCiL^{-1}$ and WL(Rn) is given in WL. Figure 4 also shows that the unattached fraction, f_u, was relatively high, up to 0.35. Low (high) values for f_u are associated with high(low) values for the aerosol concentration. This inverse relationship is not immediately obvious in Figure 4, but it has been amply documented. It should be noted that because of the relatively low radioactivity levels in the house, the values for the unattached fraction may be subject to significant statistical error.

Figures 7 to 11 show the radon daughter Working Level, WL(Rn), measured in the living room as a function of time prior to introducing any changes in the operation of the radiation control systems installed in the house. The data shown were obtained with the WLM-300, No. 064. Also shown in the graphs are the outdoor temperature and the barometric pressure. The graphs show that WL(Rn) was on the average below 20 mWL although values in excess of 30 mWL were occasionally measured.

The ratio of the maximum WL(Rn) observed to the minimum WL(Rn) observed was about 15, although occasional high values were observed. This value is not very reliable because of the large uncertainty associated with the

measurement of very low WL(Rn). The above ratio is, however quite significant in that it indicates that large fluctuations in the WL(Rn) by 'natural causes' are to be expected. These large fluctuations made analysis of the data obtained during the remedial action program quite difficult.

Figures 8 to 11 show an interesting feature, namely: an inverse dependence between WL(Rn) and outdoor temperature, T. An inverse relationship between radon gas concentration, [^{222}Rn], and outdoor temperature is also shown in Figures 12 and 13, discussed below (18). This is to be expected as radon gas is the 'precursor' of its decay products.

The effect of outdoor temperature on WL(Rn) is not observed in Figure 7 possibly because of the counteracting effect of barometric pressure (which varied in the opposite direction of T) known to inversely affect radon gas exhalation from the ground (19). It should be noted that temperature differences in excess of 18^{o}C were observed during a 16 hour period. The indoor temperature remained essentially constant throughout. Barometric pressure, however, did not vary by more than about 0.5 kPa during the same period. Hence, no large variations in [^{222}Rn] or WL(Rn) were expected because of barometric pressure changes.

Figure 12 shows the radon gas concentration and Working Level versus time. The direct relationship between [^{222}Rn] and WL(Rn) is quite evident in this case. However, this does not necessarily follow because plate-out effects, and other phenomena, can largely affect WL(Rn) while leaving the radon gas concentration unaffected.

Figure 13 shows quite a significant inverse relationship between radon gas concentration and outdoor temperature (indoor temperature remained constant). Barometric pressure variations during the same period were rather small.

Figures 14 to 26 present some of the available radiation data, i.e.,

[^{222}Rn] and WL(Rn), collected by continuous monitoring during the two-week period during which tests with different radiation control systems were in effect. Also shown in the graphs are some relevant meteorological data obtained by grab-sampling, as well as the radiation control operations that took place during the same period.

Figures 14 and 15 show the radon gas concentration measured in the laundry room and the living room versus time for the period of May 2/85 to May 7/85. It should be noted that all radiation control systems, except for the negative ion-generators (NIG), were turned on on May 1st at 17:27 hours. Hence, the [^{222}Rn] changes observed between May 2 at 12:00 h, and May 3 at 18:00 h, when all control systems were turned off, are most probably due to meteorological factors, e.g., outdoor temperature and/or wind. The relatively large decrease in radon gas concentration observed on May 2nd was possibly caused by indoor/outdoor air exchange associated with the operation in the morning of a wood-burning stove.

Figures 14 and 15 also show a large increase in radon gas concentration beginning May 3rd (Friday) at about 18:00 h, at which time all radiation control systems were turned off. This large increase was followed by a continuous decrease, with some fluctuations, until May 6th (Monday). As no information is available regarding the daily activities of the dwellers of the house during the weekend, it is not possible to draw any conclusion for this period regarding the significance of these data. However, the following should be noted:

a) the furnace was turned on for about 10 min on May 4th at 9:30 h;

b) some windows were opened during part of May 4th, and on May 5th until the early morning hours of May 6th; and

c) air intake and exhaust vents of the house were not sealed shut. Hence, indoor/outdoor air exchange was possible.

Items a, b and c may well account for the decrease in radon gas concentration on May 4th and May 5th.

Figure 15 shows a sharp increase in radon gas concentration shortly after turning the air circulation on (May 6, ~10:30 h), where fresh air was drawn into the house via an air intake vent by means of the furnace fan. At about 13:10 h, the furnace was turned on. The sharp increase in radon gas concentration on May 6th was followed by a relatively constant concentration between May 6th (17:00 h) and May 7th (9:00 h). On May 7th, the radon gas concentration began to decrease until about 19:00 h. During this period the furnace was turned off at about 11:00 h, and the air cleaner (A.C) was turned on at about 12:50 h. Furthermore, during the morning hours of May 7th, the heat in the house was turned up until 10:50 h, baking took place between 11:30 and 13:00, and some washing was done at about 15:15.

The radon gas concentration change observed between May 6th (~10:00 h) and May 7th (~19:00 h) cannot be accounted for by the operation of the radiation control systems indicated above. The changes could, however, be explained by noticing the following:

a) the windows were closed on the morning of May 6th. This could account for the increase in radon gas concentration observed shortly after for a few hours;

b) the steady increase in outdoor temperature between 10:00 h and 20:00 h on May 7th; and

c) the furnace fan was drawing air into the house via the air intake vent.

Items b and c could possibly account for the decrease in radon gas concentration observed during the morning and afternoon hours on May 7th.

There is no record of any changes introduced in the operation of the radiation control systems between May 7th (12:50 h) and May 8th (11:09 h), at which time the house ventilation system (air intake and exhaust in Table 1)

was operated. The only information on record is the use of the wood-burning stove on the morning of May 8th. The changes in the radon gas concentration measured in the evening of May 7th throughout the morning of May 8th could be due to the operation of the stove and the decrease in outdoor temperature.

Another interesting feature of Figures 14 and 15 is the relatively close profile of the radon gas concentration in the laundry room and the living room. However, there seems to be a time-lag between the times at which the maxima and minima in radon gas concentration were reached. These values for the living room were reached at some later time as compared with the times for the laundry room. Figures 14 and 15 also show that the radon gas concentration in the laundry room was somewhat higher than that for the living room. Both observations above are consistent with radon gas exhalation from the soil under the basement or basement materials and the effect of air exchange and diffusion phenomena in the house.

Figures 16, 17 and 18 show the radon daughter Working Level, WL(Rn), for the period from May 2nd (12:00 h) to May 8th (10:00 h). The radiation control operations and other activities in the house are, of course, the same as that in Figures 14 and 15.

Figure 16 shows WL(Rn) measured in the living room and in the laundry room. The graphs show a good correlation between WL(Rn) in the two rooms. It should be noted that there is a slight time-lag between WL(Rn) in the laundry room and the living room, the latter being somewhat behind the laundry room. This time-lag was also observed for the radon gas concentration, as indicated above (see also Figures 14 and 15), and is to be expected. A direct comparison of WL(Rn) in the laundry room and the living room is not possible because WL(Rn) depends on a number of variables such as aerosol concentration (e.g., cigarette smoking, cooking and baking) which may have been different for the two rooms.

A comparison between Figures 14 and 16 shows good correlation between radon gas concentration and Working Level from May 2nd (12:00 h) to May 4th (10:00 h). The WL(Rn) profile increases and decreases alternatively from the latter time on, with a tendency to even larger values. As expected, turning off all radiation control systems (May 3, ~17:00 h) brings about an increase in WL(Rn) (see also Figure 14). However, this increase is modulated in opposite fashion to the radon gas concentration. The operation of the wood-burning stove on May 4th (~9:30 h) may have compensated the effect of any air exchange (air intake and exhaust vents were not sealed shut) by an increase in aerosol concentration, which would have increased the Working Level correspondingly. However, there is no satisfactory explanation, on the basis of the data collected, to account for the behaviour of WL(Rn) as compared with the radon gas concentration.

Figures 17 and 18 show the Working Level from May 5th (14:00 h) to May 8th (10:00 h) for the living room and the laundry room, respectively. Also shown in the graphs is the aerosol concentration and other data. The correlation between the two rooms is quite good. Again, WL(Rn) values for the living room are lagging behind those corresponding to the laundry room.

It is interesting to notice that the effect of the radiation control systems in operation was either negligible or opposite to what was expected. A close inspection of the graphs, however, shows that the effect of some of the control systems was compensated by the aerosol concentration, which varied considerably from day to day and during the day, e.g., from less than 200 cm^{-3} (May 6th) to more than 2.0×10^4 cm^{-3} (May 7th). An increase(decrease) in aerosol concentration does not affect the radon gas concentration; however, it brings about an increase(decrease) in the Working Level. The reason for this is as follows. Submicron aerosols provide a substrata for the radon daughters which readily attach themselves to the aerosols, thereby reducing

their diffusivity and hence, decreasing plate-out on large surfaces, such as walls and furniture. Hence, there is a direct relationship between aerosol concentration and Working Level. However, no further increase in WL(Rn) occurs above a certain aerosol concentration, i.e., about 2.0×10^4 - 5.0×10^4 cm^{-3}, depending on other environmental conditions.

A comparison between Figures 17 and 18, and Figure 15 shows very little correlation between the Working Level and the radon gas concentration. This is so because certain control systems, and meteorological and environmental factors do not necessarily affect WL(Rn) and [^{222}Rn] the same way. However, a discussion on this subject is beyond the scope of this report. The interested reader should refer to the relevant literature on this particular topic.

Figures 19 and 20 show, respectively, the radon gas concentration and Working Level for the living room for the period May 8th to 11th, during which all radiation control systems were in operation, except the negative ion-generators, which were only operated during May 9th to May 10th. All control systems were turned off on May 10th at about 18:00 h. Hence, Figures 19 and 20 show the effect of the ion-generators during the short time they were in operation, and the effect of turning off all control systems. The effect of the negative ion generators on the Working Level (see Figure 20) is somewhat uncertain because of significant changes in the outdoor temperature and aerosol concentration during their operation. In broad terms, however, there seems to be a general tendency for the Working Level to decrease during the operation of the generators, other environmental factors notwithstanding. The changes in radon gas concentration during the same period are related to environmental factors, as discussed previously. There is a fair correlation between the radon gas concentration (Figure 19) and the Working Level (Figure 20), except for some time-lag observed for the latter. The large increase in both Working Level and radon gas concentration, observed after about 18:00 h

on May 10th was caused by turning off the radiation control systems. However, the variable behaviour, i.e., transient effect, observed after 8:00 h on May 11th is not clearly understood, although it is partly related to the effect of environmental factors. As no information is available on the house and occupant activities during the weekend (May 10th to May 11th), no conclusions can be drawn regarding this transient behaviour.

Figure 21 shows the radon gas concentration and the Working Level in the laundry room during the period May 8th to 11th. Comparison of Figures 19 and 21 shows a fairly good correlation between the radon gas concentration in the living room and the laundry room, respectively. The Figures also show that the radon concentration in the laundry room was higher than in the living room, as expected. Good correlation was also found between the Working Level in the living room (Figure 20) and the laundry room (Figure 21). As for the radon gas, the Working Level in the laundry room was significantly higher than in the living room. The same general considerations discussed for Figures 19 and 20, apply equally well to Figure 21.

Figure 22 shows the radon gas concentration and the Working Level in the living room for the period May 11th to May 14th. During May 11th to May 13th all radiation control systems were turned off. At about 17:00 h on May 13th, the negative ion generators were turned on. For some period in the afternoon of May 13th, a sliding door was opened and the kitchen exhaust fan was operated. Large fluctuations in the Working Level and radon gas concentration were observed, most likely due to a combination of meteorological and environmental factors, and activities in the house, of which no information is available. Hence, the effect of the negative ion generators on the Working Level cannot accurately be ascertained. It should be noted that during this period, the radon gas concentration continued to increase up to the early hours of the following morning, at which time the

concentration started to decrease rapidly (see Figure 24). Since opening the sliding door and operating the kitchen exhaust fan should equally have affected the radon gas concentration and the Working Level, it is suggested from the data in Figure 22 that the decrease in Working Level may partly be due to the operation of the ion-generators.

Figure 23 shows the radon gas concentration and Working Level in the laundry room for the same period as that of Figure 22 corresponding to the living room. There is, in general, a reasonable correlation between the radon gas concentration and the Working Level, as shown by this graph. It should be noted that the opening of the door, and the operation of the kitchen exhaust fan, on the living room level, should not unduly affect the radiation levels in the laundry room. Hence, the effect of the negative ion generators operating in the laundry room should show more clearly in the latter than in the living room. The data in Figure 23 show, however, that if the ion generators had any effect on the Working Level in the laundry room, it took about 8 h to become evident. There is a reasonable correlation between the radiation levels indicated by Figures 22 and 23.

Figures 24 and 25 show, respectively, the radon gas concentration and Working Level in the living room during the period of May 14th to May 17th, at which time the tests were terminated. The effect of the circulation on the radon gas concentration was quite evident. This effect on the Working Level appears with a substantial delay (see Figure 25). The effect of the ventilation on the radon gas concentration and the Working Level is quite pronounced, as shown in both Figures. The effect of the air cleaner on the Working Level (see Figure 25) is also quite significant. There is only partial correlation between radon gas concentration and Working Level as shown when Figures 24 and 25 are compared.

Figure 26 shows the radon gas concentration and Working Level in the

laundry room for the same period of time as that for the living room (see Figures 24 and 25). Correlation of the radon gas concentration and the Working Level for the living room and the laundry room is fairly good. In addition, the same general considerations and conclusions regarding Figures 24 and 25, i.e., living room, apply equally well to the laundry room.

Figures 27 to 30 show the daily values averaged over a period of 24 h/day, for the radon gas concentration and the Working Level in the living room and the laundry room during the period April 12th to May 17th, 1985. These graphs include most of the data gathered during the entire monitoring period in the house, namely the period for compliance purposes in which all the control systems, except the ion-generators, were on continuously (20), i.e., up to May 1st, followed by the remedial action program, subject of this report, where the individual effect of each of the different control systems, and all the systems together, were investigated. It should be noted that the data on Figures 27 to 30 have been obtained by averaging the hourly values given by the instruments, i.e., each value on the graph represents the average of 24 readings per day, as data are collected on an hourly basis.

The above Figures show two quite distinctive regions, namely: one region with nearly-constant radiation levels during the compliance period, and a region over which radiation levels vary substantially on a daily basis, mostly due to the effect of the systematic study of the different radiation control measures investigated.

Figures 27 and 28 show the radon gas concentration and Working Level in the living room and laundry room, respectively. The graphs show that both the radon gas concentration and Working Level are higher in the laundry room (basement) than in the living room. This is partly indicative of stratification caused by insufficient or partial air mixing in the dwelling. Figures 28 and 27 also show that a slightly better correlation for the Working

Level was found between the living room and the laundry room than for the radon gas concentration in the same areas. This result may, however, not be very significant and subject to revision.

Figures 29 and 30 show the radon gas concentration and Working Level, respectively, in the living room and laundry room. The graphs show that there is a reasonable correlation between these two variables. Discrepancies arise partly from the different way the implemented control measures affect radon gas and radon daughters. The time-lag corresponding to radon gas relative to the Working Level may reflect this situation, combined with the effect of meteorological and environmental factors, and habits and activities in the dwelling, which are also known to affect radon gas and radon daughters differently.

CONCLUSIONS AND REMARKS

The data presented in this report show quite significant variations in radon and radon daughter concentration levels in the house under study during the monitoring period. These variations have three different and unrelated origins, namely:

1. Meteorological, e.g., outdoor temperature, wind velocity, and possibly other climatological conditions including rain and soil temperature.

Rain permeating the soil dissolves radon which can gain access to the basement of the house through, say, a weeping tile system partly discharging into a sump pump/drainage system in the basement. Soil temperature can affect its physical characteristics, i.e., porosity and permeability, thereby affecting the diffusion and transport of radon.

In the present case, changes in the radiation level originating from soil temperature variations can safely be ignored because monitoring was not conducted over periods long enough for any appreciable temperature difference

to develop. The effect of wind velocity, on the other hand, has not yet been investigated here. Furthermore, there was practically no appreciable rainfall during the months of April and May, 1985.

The data presented in this report clearly show the (inverse) effect of outdoor temperature on airborne radiation levels in the house. This effect is caused by air leakage and air currents, and hence air-exchange, set up through, and across, cracks, openings, and porous walls in the house due to temperature differentials arising between outdoor and indoor temperature conditions. It should be noted that indoor temperature can be considered essentially constant and in the range 18-20^{o}C.

2. Dwellers Habits and House Activities These include washing (laundry), house cleaning (vacuuming, dusting), cooking and baking, heating, smoking, window/door opening and closing, and a host of other activities. The above habits and/or activities are known to affect several important environmental factors such as indoor temperature and relative humidity, aerosol composition, aerosol concentration, aerosol size distribution, and tracer gas concentration. These factors have a significant influence on plate-out phenomena, i.e., rate of attachment and deposition of radioactive aerosol, and hence on the attached and unattached radon daughter fractions, which in turn affect radon daughter concentration levels.

Information on the above habits and activities during the monitoring period is sparse as the dwellers preferred not to disclose some of the much needed and important information. Hence, their effect on the radiation level cannot adequately be ascertained.

3. Control Systems for Remedial Purposes From all the control systems investigated, the most effective one in reducing radon daughter concentration levels was ventilation followed by air cleaning, i.e., removal of radon daughter products, by the electronic air 'cleaner'. The effect of air mixing

fans and ion-generators was somewhat limited because of the reduced number of operating units in relation to the total volume of air to be cleaned. Furthermore, the ion-generators used in this study were not efficient enough as the ion-concentration attained in room air after sustained operation rarely exceeded 10^4 cm^{-3}. It should be noted that the latter two control systems, i.e., mixing fans and ion-generators have proved quite efficient in reducing radon and thoron decay products in controlled environments (7,8).

As expected, the only effective method of reducing radon gas concentration levels was ventilation. The other systems are only effective in removing radon daughters.

In summary, meteorological variables (outdoor temperature) had a strong effect on radiation levels. The combined effect on the radiation level from meteorological factors, and one or more of the control systems, was at times difficult to ascertain. The combined effect was strongly dependent on the control system, or systems, operated at the time and the direction and intensity of the changing meteorological variable. Quite often the combined effect was masked by the dweller's living habits and activities carried out in the house, of which sparse information is available.

During periods in which meteorological activity remained essentially constant, the effect of the control systems was clear and as indicated in item 3.

It is clear, from the data presented here, that the two week period available for monitoring the effect of the control systems on the radiation level in the house, is insufficient. As expressed by AECL, one of the main objectives of the study was to carry out a monitoring program under actual living conditions. However, the lack of pertinent data regarding the living habits of the occupants of the house, and the wide range of activities conducted in the house, on one hand, and the practical difficulty in

eliminating the effect of meteorological variables, on the other hand, makes analysis of the effect of control systems for remedial purposes rather difficult. A more complete study would require a much longer period. This would allow a more frequent and thorough testing of the control systems under more favourable, i.e., constant, meteorological conditions.

ACKNOWLEDGEMENTS

This investigation was requested by Atomic Energy of Canada Ltd (AECL). The author is grateful to R. Pollock and B. McCallum (AECL) for the facilities provided and frequent discussion throughout this work. Mr. Lalonde (Co-op student, Waterloo University) was delegated by AECL to work on this project. Thanks are extended to D. Desrochers (DMSA) who was responsible for conducting most of the experimental work reported here. The assistance of S. Brown (COSEP student, Sault College of Technology and Applied Arts) is gratefully acknowledged.

REFERENCES

1. Bruno, R.C., "Sources of indoor radon in houses: a review"; J. Air Pollution Control Assoc., vol. 33, No. 2, pp 105-109; 1983.

2. Stranden, E., Berteig, L. and Ugletveit, F., "A study on radon in dwellings"; Health Physics, vol 36, pp 413-421; 1979.

3. Stranden, E. and Berteig, L., "Radon in dwellings and influencing factors"; Health Physics, vol 39, pp 275-284; 1980.

4. Holub, R.F., Droullard, R.F., Ho, W., Hopke, P.K., Parsley, R. and Stukel, J.J., "The reduction of airborne radon daughter concentration by plate-out on an air mixing fan"; Health Physics, vol 36, p 497; 1979.

5. Schreve, J.D. Jr. and Cleveland, J.E., "Effects of depressing attachment

ratio of radon daughters in uranium mine atmospheres"; Am. Ind. Hyg. Assoc. J., vol 33, p 304; 1972.

6. Wrenn, M.E., Eisenbud, M., Costa-Ribeiro, C., Hazle, A.J. and Siek, R.D., "Reduction of radon daughter concentrations in mines by rapid mixing without make-up air"; Health Physics, vol 17, p 405; 1969.

7. Bigu, J., "On the effect of a negative ion-generator and a mixing fan on the plate-out of radon decay products in a radon box"; Health Physics, vol 44, pp 259-266; 1983.

8. Bigu, J. and Grenier, M.G., "On the effect of a negative ion-generator and a mixing fan on the attachment of thoron-decay products in a thoron box"; Health Physics, vol 46, pp 933-939; 1984.

9. Bigu, J., "Calibration of the pylon AB-5/EL and AB-5/PRD systems, two continuous radon gas monitors", Division Report M&ET/MRL 86-65(TR), CANMET, Energy, Mines and Resources Canada; March 1986.

10. Cowper, G., "Radiation dosimetry and instrumentation development"; AECL Technical Report CRNL/AECL-4;

11. Kusnetz, H.L., "Radon daughters in mine atmospheres"; Am. Ind. Hyg. Assoc. J., vol 17, p 1; 1956.

12. Scott, A.G., "A field method for measurement of radon daughters in air"; Health Physics, vol 41, p 403; 1981.

13. Bigu, J., "Calibration of the pylon AB-5/AEP system, a continuous radon daughter working level monitor"; Division Report M&ET/MRL 86-64(TR); CANMET, Energy, Mines and Resources Canada; February 1986.

14. James, A.C., Bradford, G.F. and Howell, D.M., "Collection of unattached RaA atoms using a wire gauze"; J. Aerosol Science, vol 3, pp 243-254; 1972.

15. George, A.C., "Measurement of the uncombined fraction of radon daughters

with wire screens"; Health Physics, vol 23, p 390; 1972.

16. Raghavayya, M. and Jones, J.H., "A wire-screen-filter-paper combination for the measurement of fractions of unattached daughter atoms in uranium mines"; Health Physics, vol 26, p 417; 1974.

17. Rudnick, S.N., Hinds, W.C., Maher, E.F. and First, M.W., "Effect of plateout, air motion and dust removal on radon decay product concentration in a simulated residence"; Health Physics, vol 45, pp 463-470; 1983.

18. Kotrappa, P., Mayya, Y.S., Dua, S.K. and Gupta, P.C., "Increase in ground level concentration of radon during a solar eclipse"; Health Physics, vol 40, pp 559-560; 1981.

19. Clements, W.E. and Wilkening, M.H., "Atmospheric pressure effects on Rn-222 transport across the earth-air interface"; J. Geophys. Res., vol 79., pp 5025-5029; 1974.

20. DSMA Atcon Ltd., "Radon and radon daughter levels and the effectiveness of remedial measures in selected Elliot Lake buildings: phases I, II and III"; vol. 1 and 2; DMSA Atcon Ltd. Report to AECL; August 1985.

Table 1 - Test schedule during implementation of the different radiation control systems program.

Time Period	TEST CONDITION Electronic Air Cleaner	Furnace Fan Circulation	Air Intake and Exhaust	Negative Ion Generator	Remarks
850402-850501 17:27	ON	ON	ON	OFF	See data before implementation of radiation control systems program.
850501-850503 17:27 17:52	ON	ON	ON (heater off)	ON	Bionaire 100A NIG on laundry room freezer located ∿2.5 m from monitors. Wood stove in use morning of 850502.
850503-850506 17:52 13:11	OFF	OFF	OFF	OFF	Air intake and exhaust vents NOT sealed shut. Furnace on for 10 min. 850504 at 9:30. Windows opened 850504 and 5, all closed a.m. of 850506.
850506-850507 13:11 12:48	OFF	ON	OFF	OFF	Furnace fan drawing air into house via air intake vent. Heat turned up during morning of 850507 until 10:50.
850507-850508 12:48 11:09	ON	ON	OFF	OFF	Furnace fan drawing air into house via air intake vent; baking 11:30 - 13:00, washing ∿15:15.
850508-850509 11:09 11:16	ON	ON	ON	OFF	Wood stove in use morning of 850508 all windows closed; vacuuming 850509 10:05-10:25.
850509-850510 11:16 17:51	ON	ON	ON	ON	Bionaire 2000 NIG in living room ∿4 m from monitors. Bionaire 100A NIG in laundry room ∿3 m from monitors. Windows open all day and door open from 16:45 on 850510.
850510-850513 17:51 17:23	OFF	OFF	OFF	OFF	Air intake and exhaust vents taped shut. Door opened at 850513 16:30. Cooking 850513 17:00 to 17:30.
850513-850514 17:23 11:52	OFF	OFF	OFF	ON	Bionaire 2000 & 500s NIGs in living room ∿4 m from monitors. Pollenex & Bionaire 100A NIG's in laundry room ∿2.5 m from monitors.
850514-850515 11:52 12:16	OFF	ON	OFF	ON	Air vents still taped shut. All windows & doors closed.
850515-850516 12:16 13:40	OFF	ON	ON	ON	Air vents opened.
850516-850517 13:40 ∿11:30	ON	ON	ON	ON	

Table 2 - Radiation data collected before the implementation of the different radiation control systems program

LOCATION	LIVING ROOM		LAUNDRY ROOM	
Method	Monitoring Period(s)	WL,mWL Mean (SD%)	Monitoring Period(s)	WL,mWL Mean (SD%)
Grab-sampling	850402-850501	15 (65)	850402-850501	16 (46)
Pylon AB-5	-	-	850412-29; 850430-0502	21.8 (1.4)
EDA WLM-300	850417-850501	11.4	-	-
MOD-225	-	-	850402-850501	16
MOL	850402-850501	13 (17)	850402-850501	18 (27)
		[Rn-222],$pCiL^{-1}$ Mean (SD%)		
Grab-sampling	850402-850501	9.5 (50)	850402-850501	15.4 (38)
Pylon AB-5	850424-850501	12.1 (14.7)	850412-22, 24-29, 850430-850501	24.7 (18.1)
Terradex	850402-850501	11.9 (37)	850402-850501	14.5 (8)
NRPB	850402-850501	13.9 (5)	850402-850501	19.2(27)
PRIM (CaF_2)	850402-850501	17	850402-850501	7
PRIM (LiF)	850402-850501	9	850402-850501	18

Table 3 - Data for several variables before the implementation of the different radiation control systems program (mean values and standard deviation).

Location	Monitoring Period(s)	WLR	$N(10^{-3})$ cm^{-3}	Q h^{-1}	RH %	T_{indoor} °C	$T_{outdoors}$ °C	P kPa
Living room	850402-850501	0.16 (36)	15.5 (149)	0.57	30 (25)	24 (8)	5.2 (137)	97.1 (1)
Laundry room	850402-850501	0.12 (34)	26.4 (103)	0.57	39 (14)	20 (4)	5.2 (137)	97.1 (1)

Table 4 - Maximum, minimum and mean values for several variables measured by grab-sampling before the implementation of the different radiation control systems program.

Variable	Minimum Value	Maximum Value	Mean Value	Standard Deviation %	Location
WL, mWL	2.0	37.0	15.0	65	Living room
"	5.0	35.0	16.0	46	Laundry room
[Rn-222], $pCiL^{-1}$	1.3	15.0	9.5	50	Living room
" "	3.5	21.6	15.4	38	Laundry room
WLR	0.09	0.25	0.16	36	Living room
"	0.05	0.18	0.12	34	Laundry room
$N(10^{-3})$, cm^{-3}	2.1	92.7	15.5	149	Living room
" "	2.1	100.0	26.4	103	Laundry room
T_{wb}, °C	11.3	16.8	13.8	13	Living room
" "	10.9	16.1	12.8	14	Laundry room
T_{db}, °C	20.5	26.0	23.9	8	Living room
" "	18.8	21.8	20.3	4	Laundry room
RH, %	18.5	41.0	30.0	25	Living room
" "	32.0	60.0	41.0	21	Laundry room
Q, h^{-1}	0.51	0.63	0.57	-	Living room
" "	0.51	0.63	0.57	-	Laundry room

Table 5 - Maximum, minimum and mean values for several variables measured by grab-sampling during the implementation of the different radiation control systems program.

Variable	Minimum Value	Maximum Value	Mean Value	Standard Deviation	Location
[Rn-222], $pCiL^{-1}$	0.47	62.6	30.12	17.26	Laundry room
" "	0.17	59.4	24.87	14.51	Living room
WL(Rn), mWL	1.0	206.0	66.00	55.18	Laundry room
" "	1.0	150.0	61.13	47.02	Living room
WLR	0.08	0.44	0.20	0.09	Laundry room
"	0.10	0.60	0.24	0.13	Living room
[RaA], $pCiL^{-1}$	0.60	45.22	18.28	12.51	Laundry room
" "	0.40	37.59	16.02	9.83	Living room
[RaB], $pCiL^{-1}$	0.14	19.94	6.02	5.34	Laundry room
" "	0.85	14.52	6.07	4.54	Living room
[RaC], $pCiL^{-1}$	0.04	16.91	4.46	4.75	Laundry room
" "	0.15	12.25	4.41	4.02	Living room
X^1	0.12	0.59	0.30	-	Laundry room
"	0.14	0.54	0.33	-	Living room
Y^2	0.06	0.71	0.21	-	Laundry room
"	0.03	0.57	0.22	-	Living room
$f_{,\mu}$	0.02	0.36	0.23	0.10	Laundry room
"	0.15	0.31	0.23	0.05	Living room
$N(10^{-3})$, cm^{-3}	1.2	22.0	6.21	5.97	Laundry room
"	0.7	16.7	5.28	4.27	Living room
Q, h^{-1}	0.2	0.66	-	-	Laundry room
" "	0.2	0.66	-	-	Living room

[1]X stands for the ratio [RaB]/[RaA].

[2]Y stands for the ratio [RaC]/[RaA].

Note: RaA, RaB and RaC stand, respectively, for ^{218}Po, ^{214}Pb and ^{214}Bi.

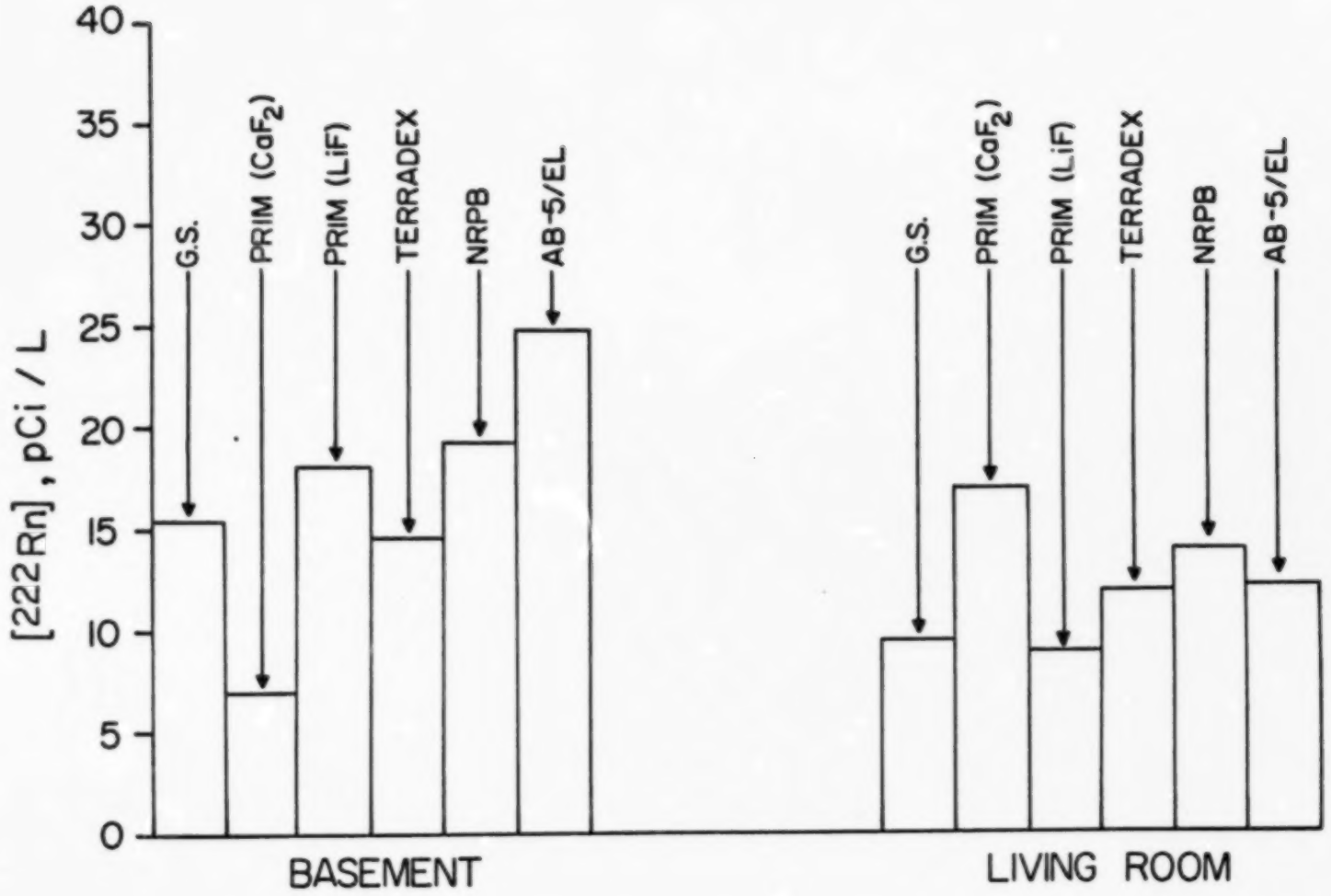

Fig. 1 - Radon gas concentration as determined by several methods, techniques, and instrumentation. Data represent average values obtained before the radiation control systems program.

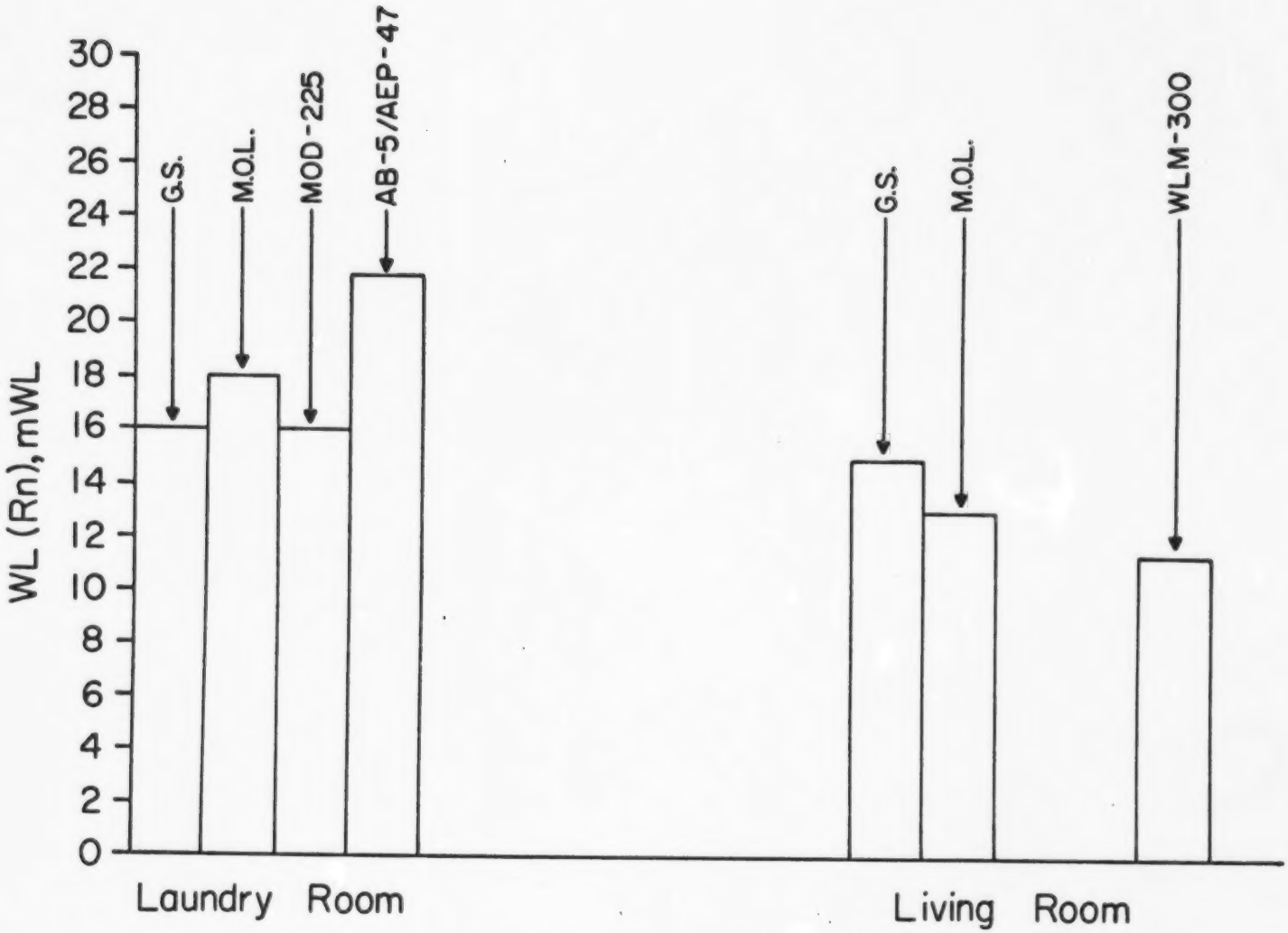

Fig. 2 - Radon daughter Working Levels as determined by several methods, techniques and instrumentation. Data represent average values obtained before the radiation control systems program.

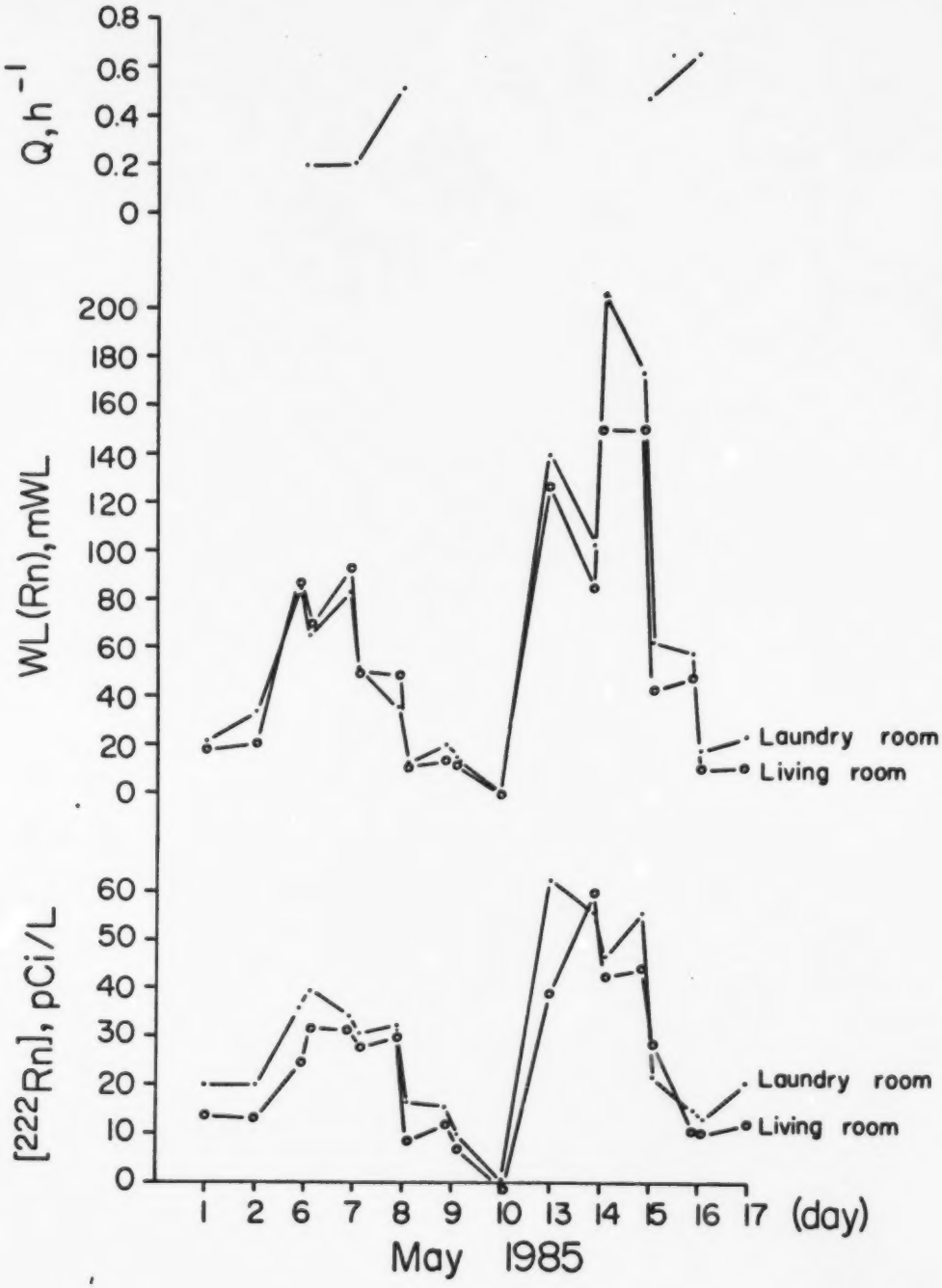

Fig. 3 - Radon gas concentration, radon daughter Working Level, and ventilation rate (Q) versus time.

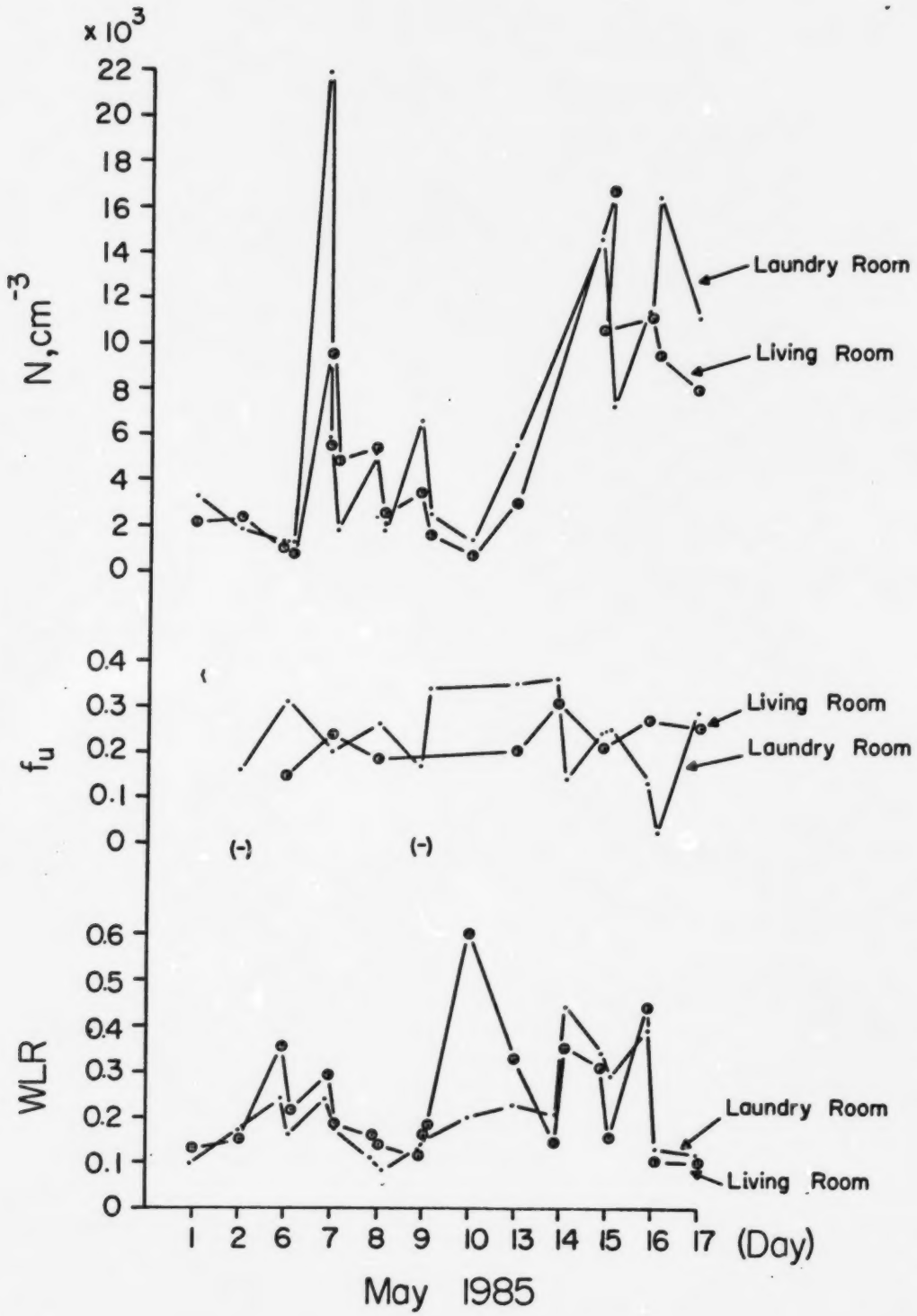

Fig. 4 - Working Level ratio (WLR), unattached fraction (f_u), and aerosol concentration (N) versus time.

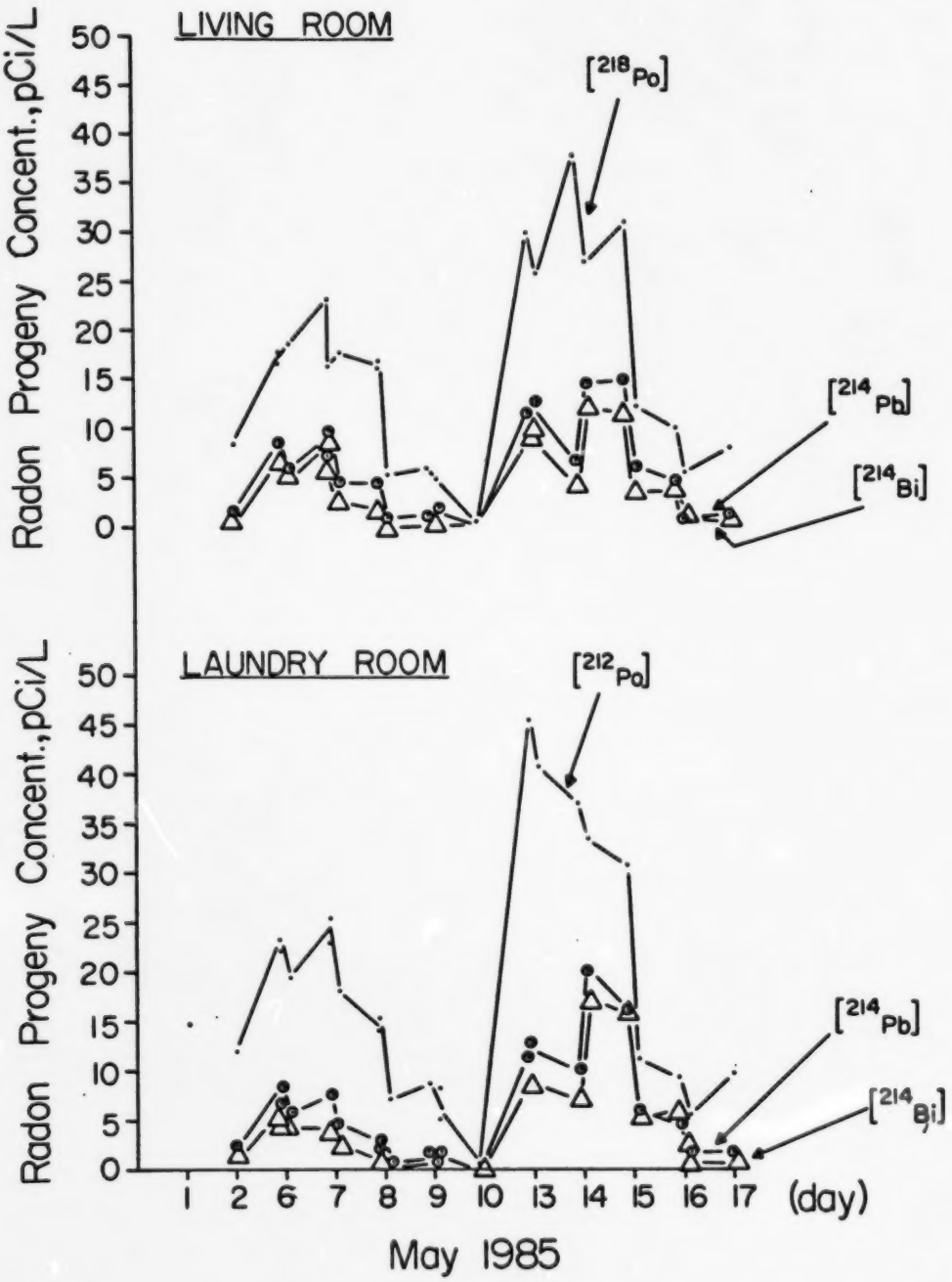

Fig. 5 - Radon progeny concentration versus time.

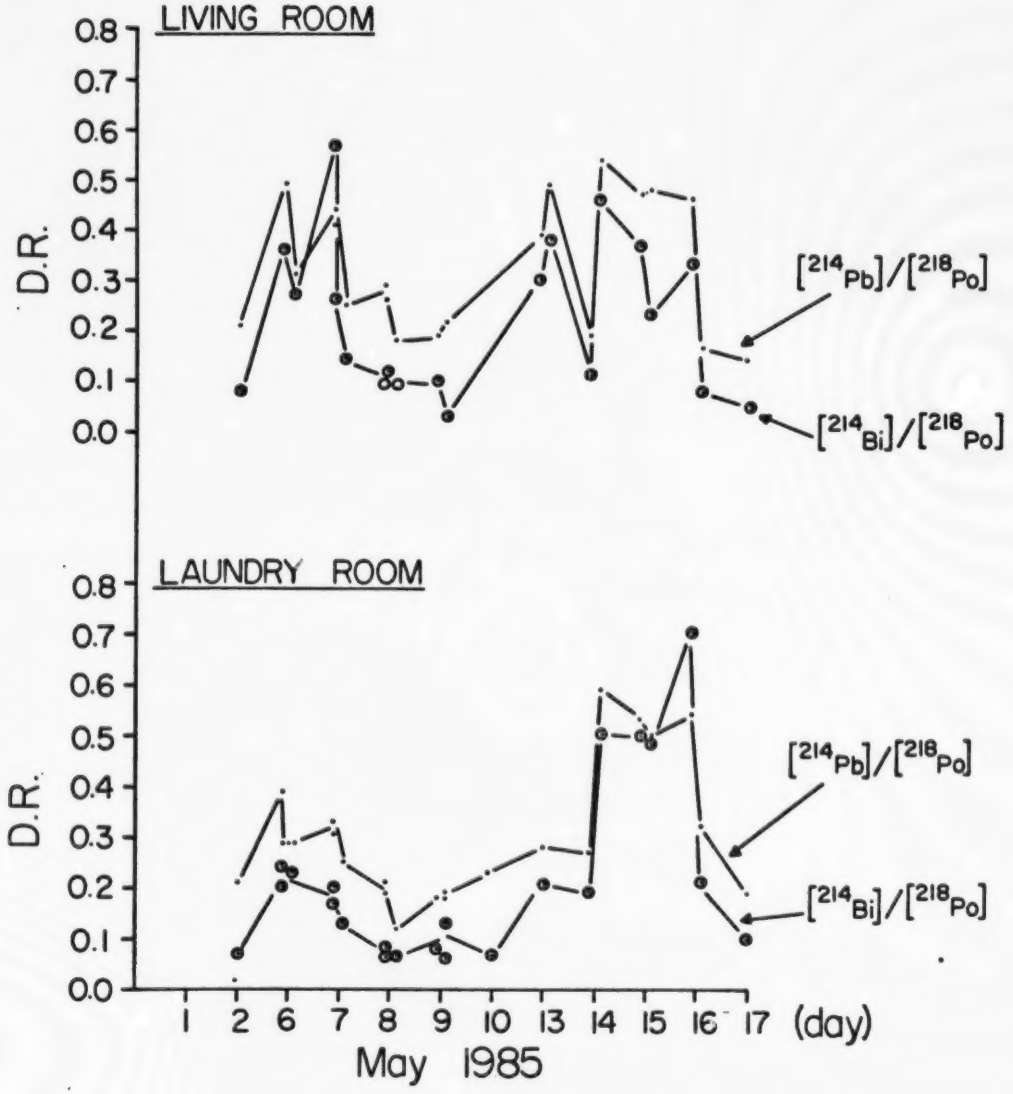

Fig. 6 - Disequilibrium ratio (D.R.) versus time.

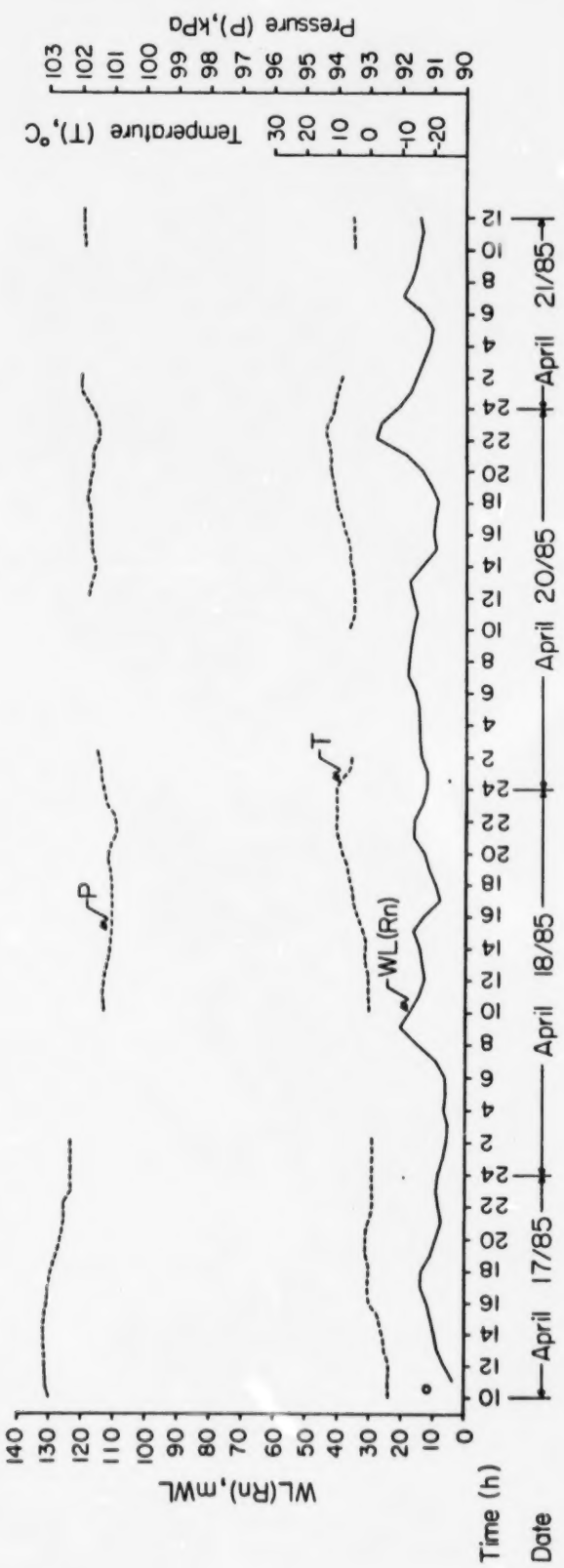

Fig. 7 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T) and Pressure (P). Data taken in the living room.

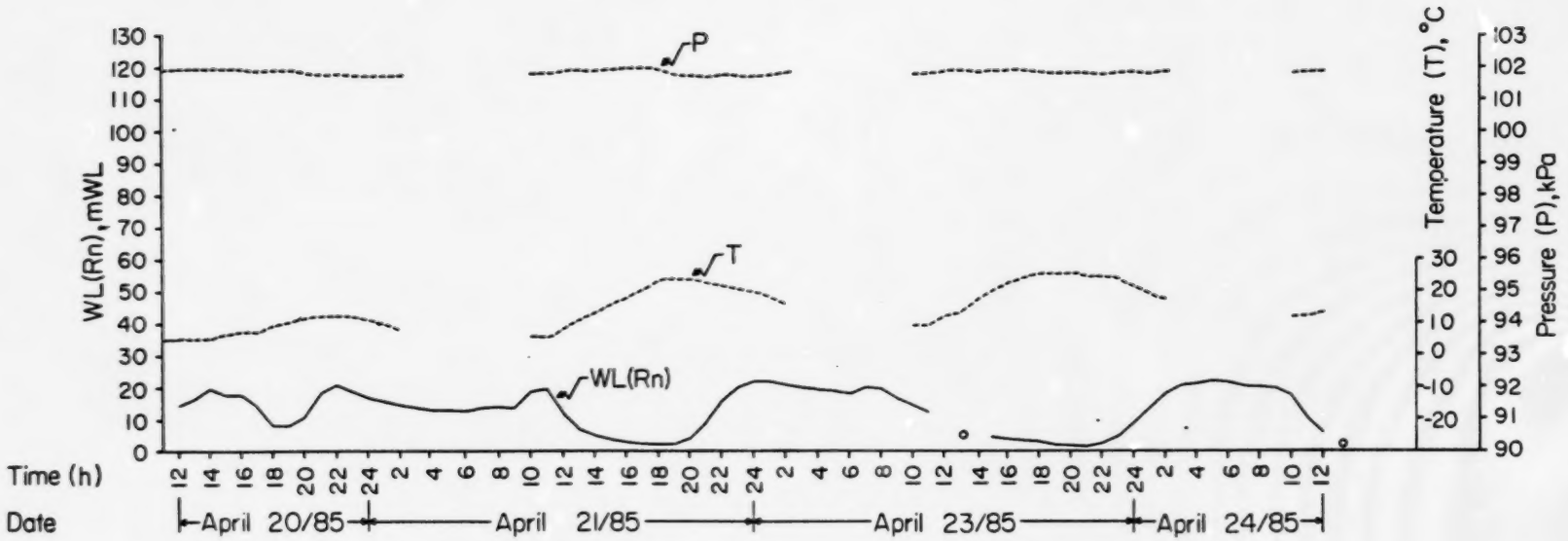

Fig. 8 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T) and Pressure (P). Data taken in the living room.

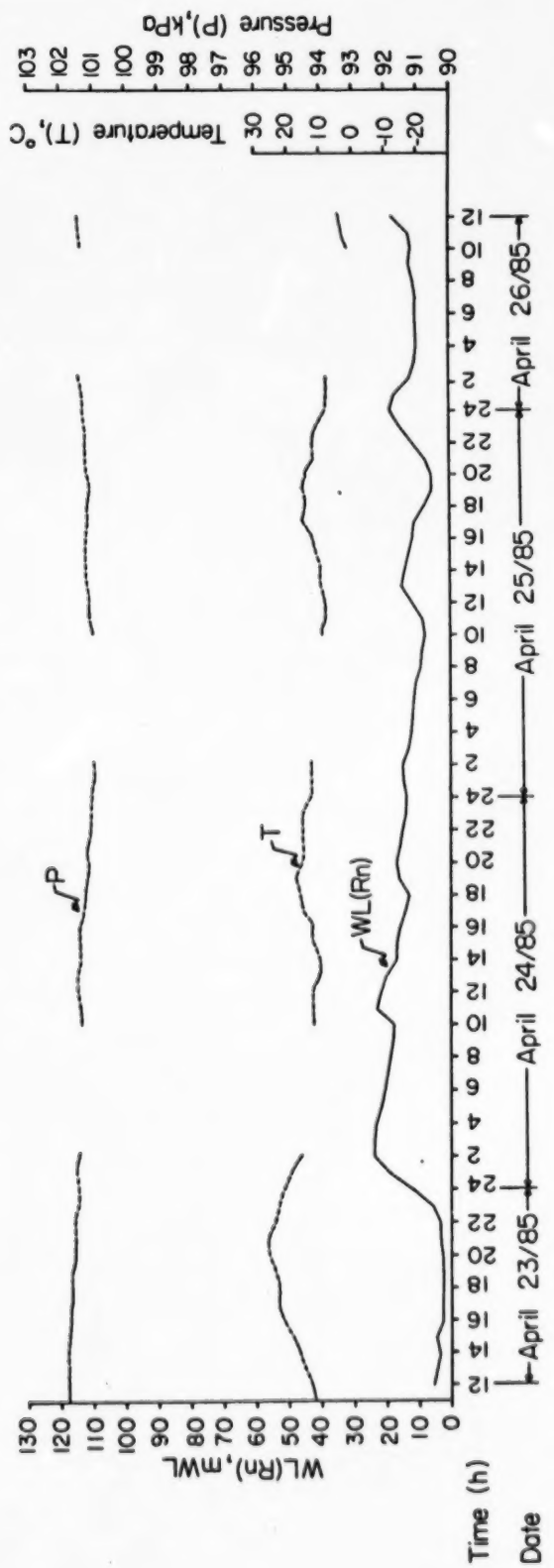

Fig. 9 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T) and Pressure (P). Data taken in the living room.

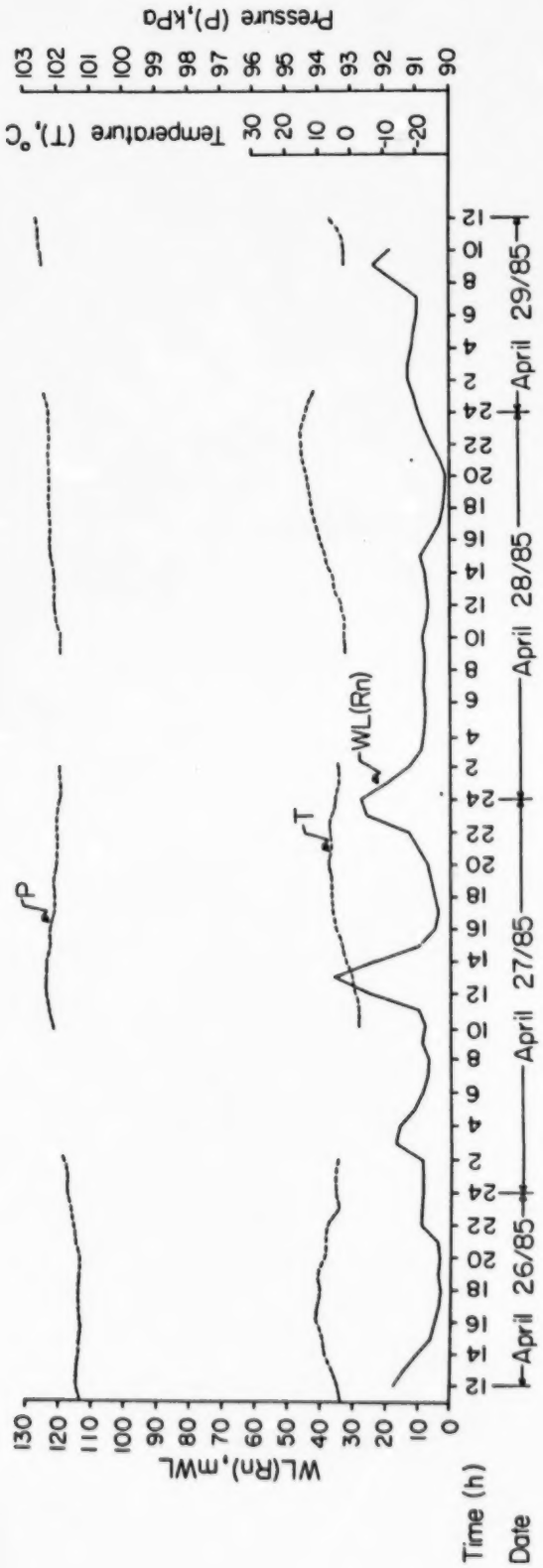

Fig. 10 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T) and Pressure (P). Data taken in the living room.

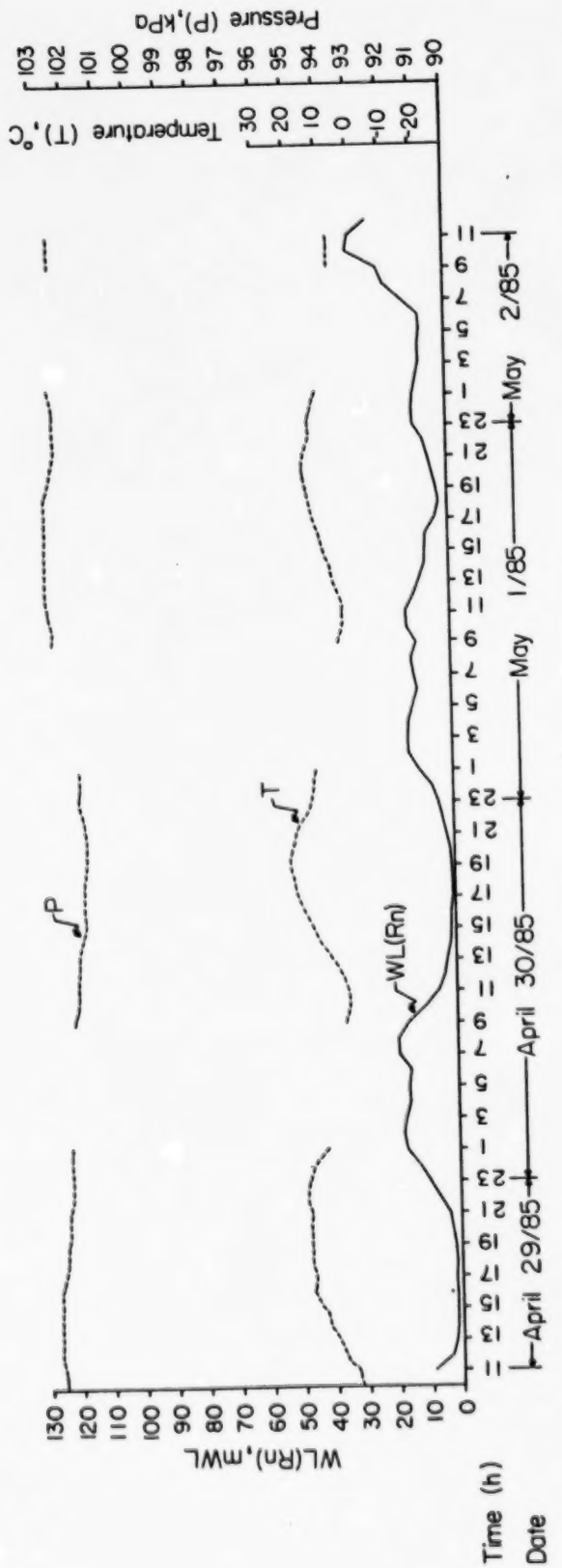

Fig. 11 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T) and Pressure (P). Data taken in the living room.

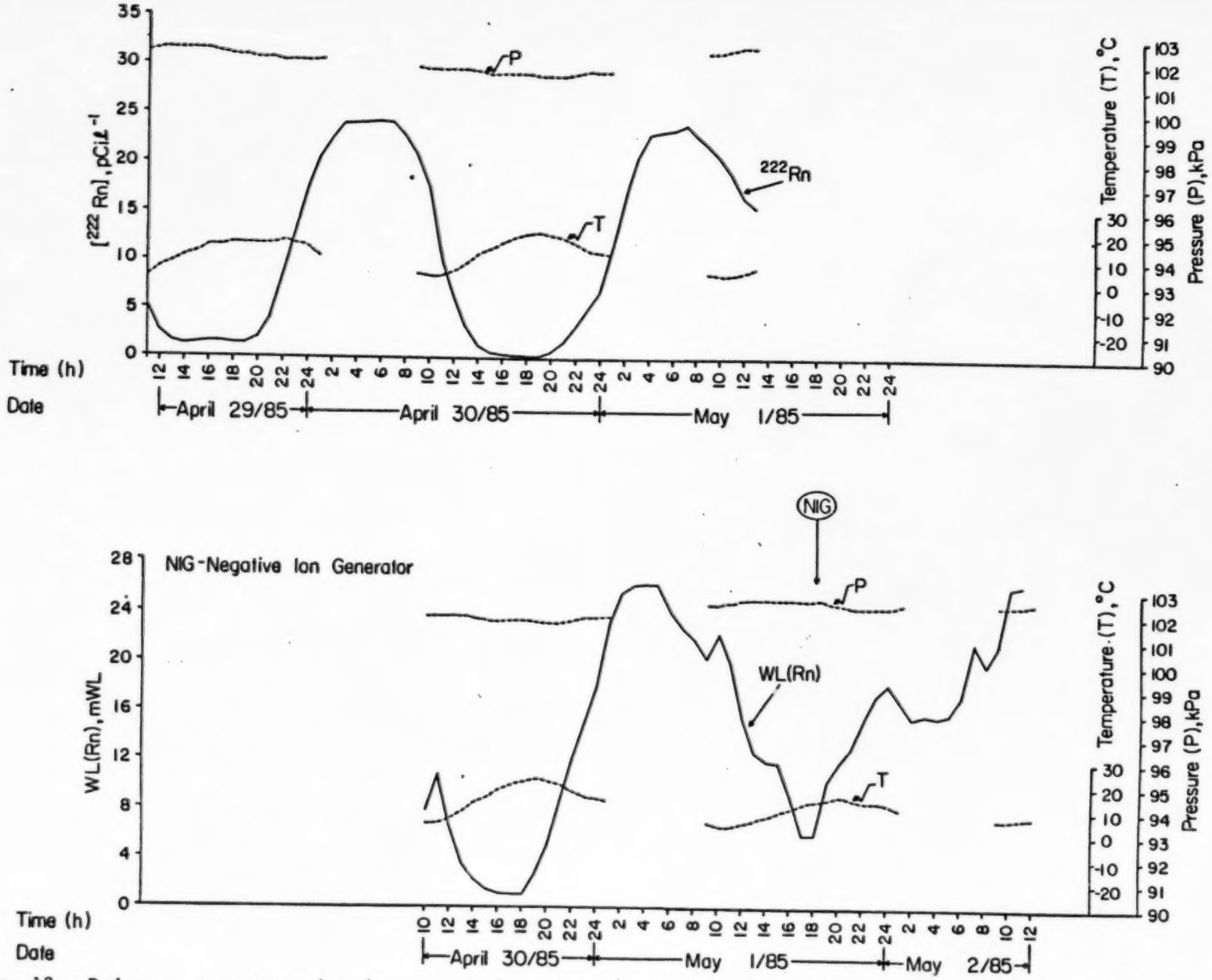

Fig. 12 - Radon gas concentration (upper curve), and radon daughter Working Level (lower curve) versus time. Also shown are the outdoor temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the living room (upper curve), and in the laundry room (lower graphs).

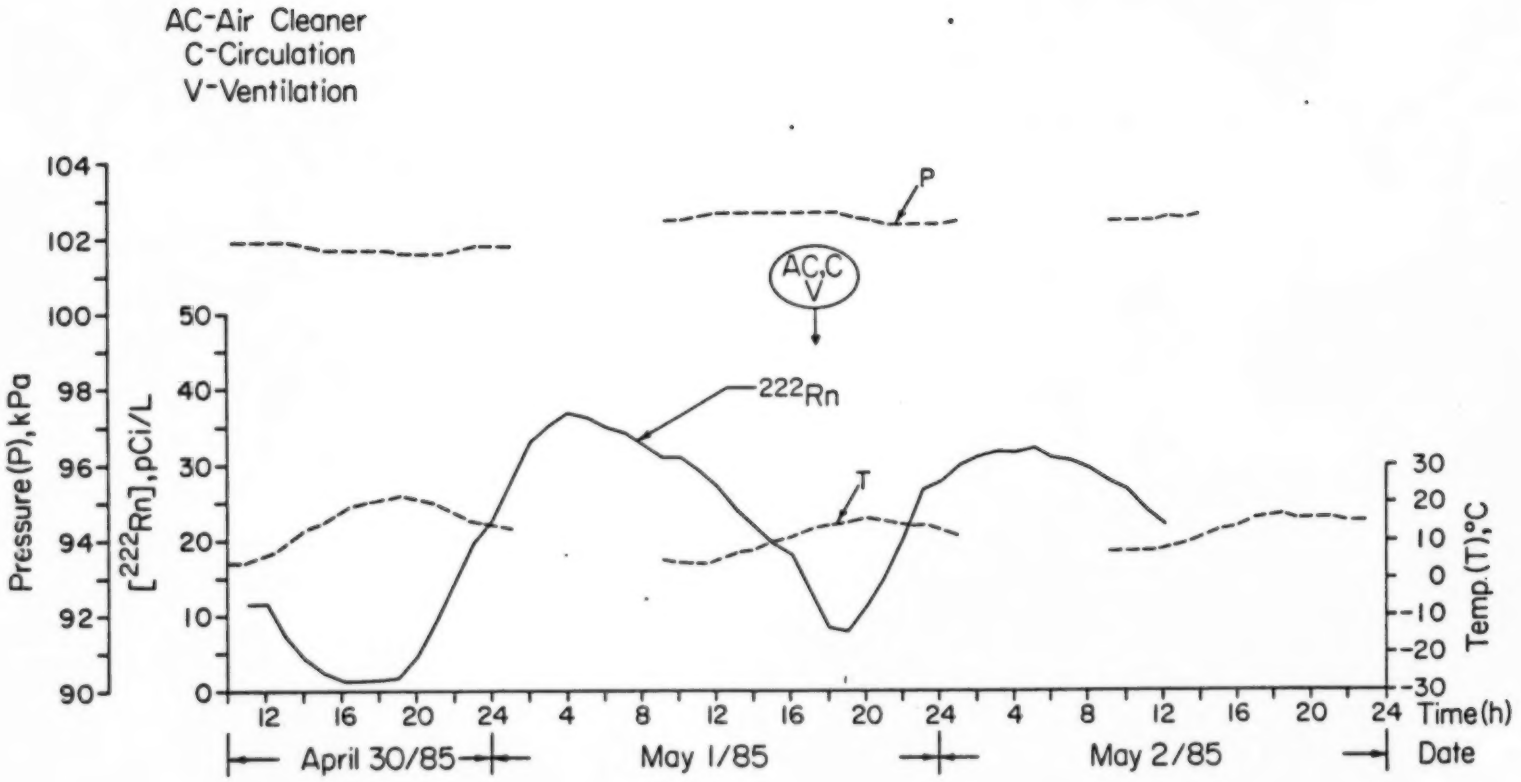

Fig. 13 - Radon gas concentration versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the laundry room.

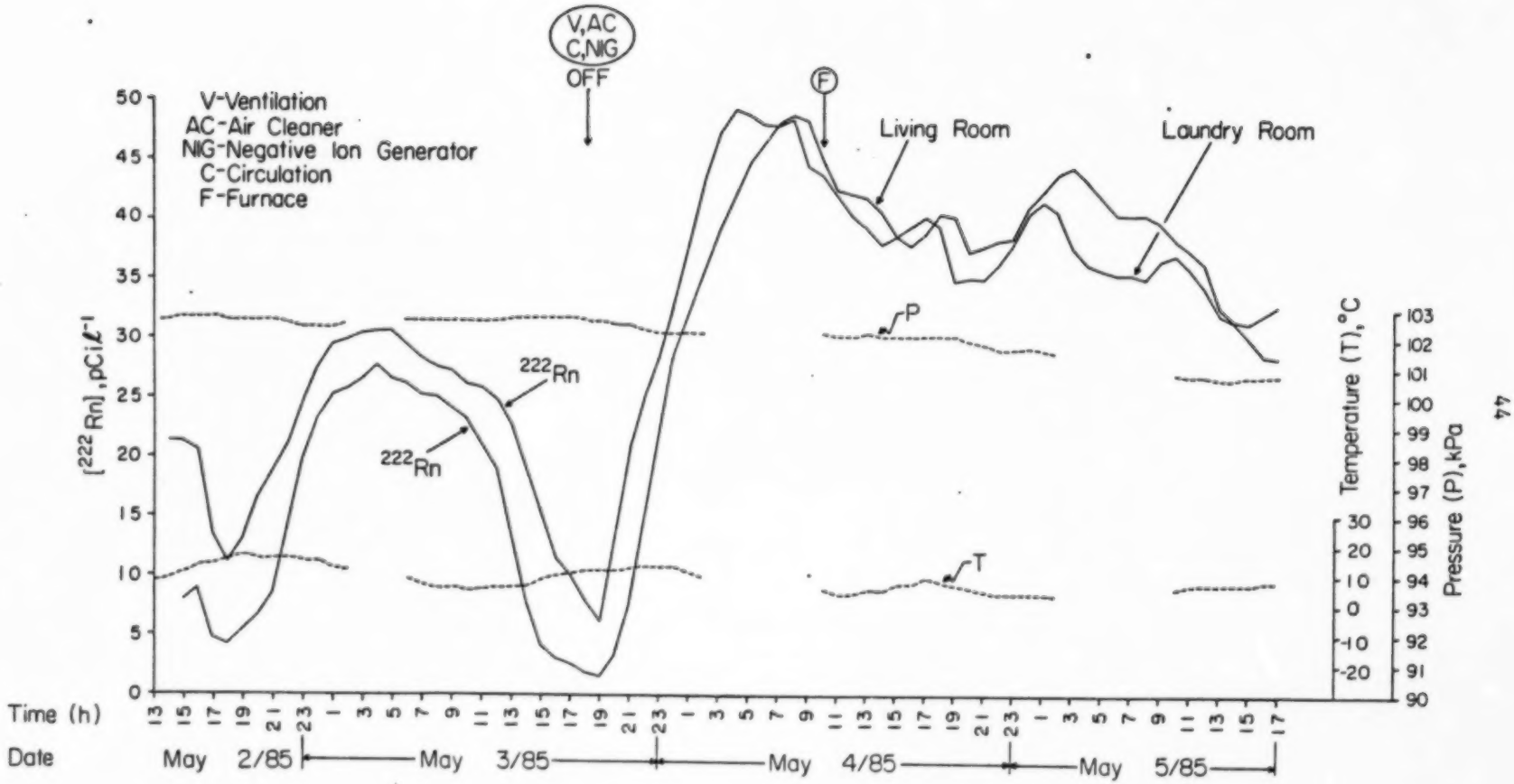

Fig. 14 - Radon gas concentration versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows.

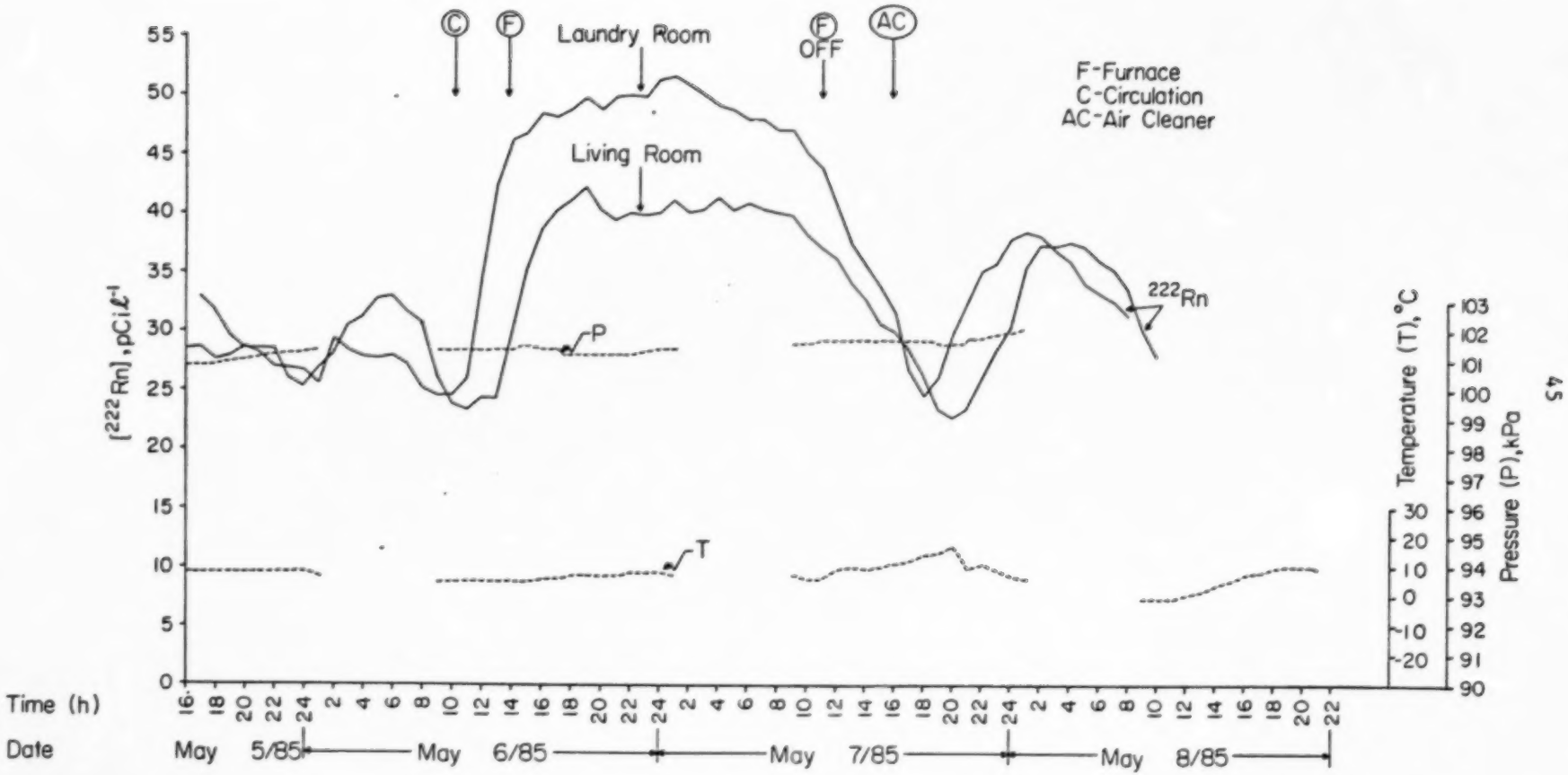

Fig. 15 - Radon gas concentration versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows.

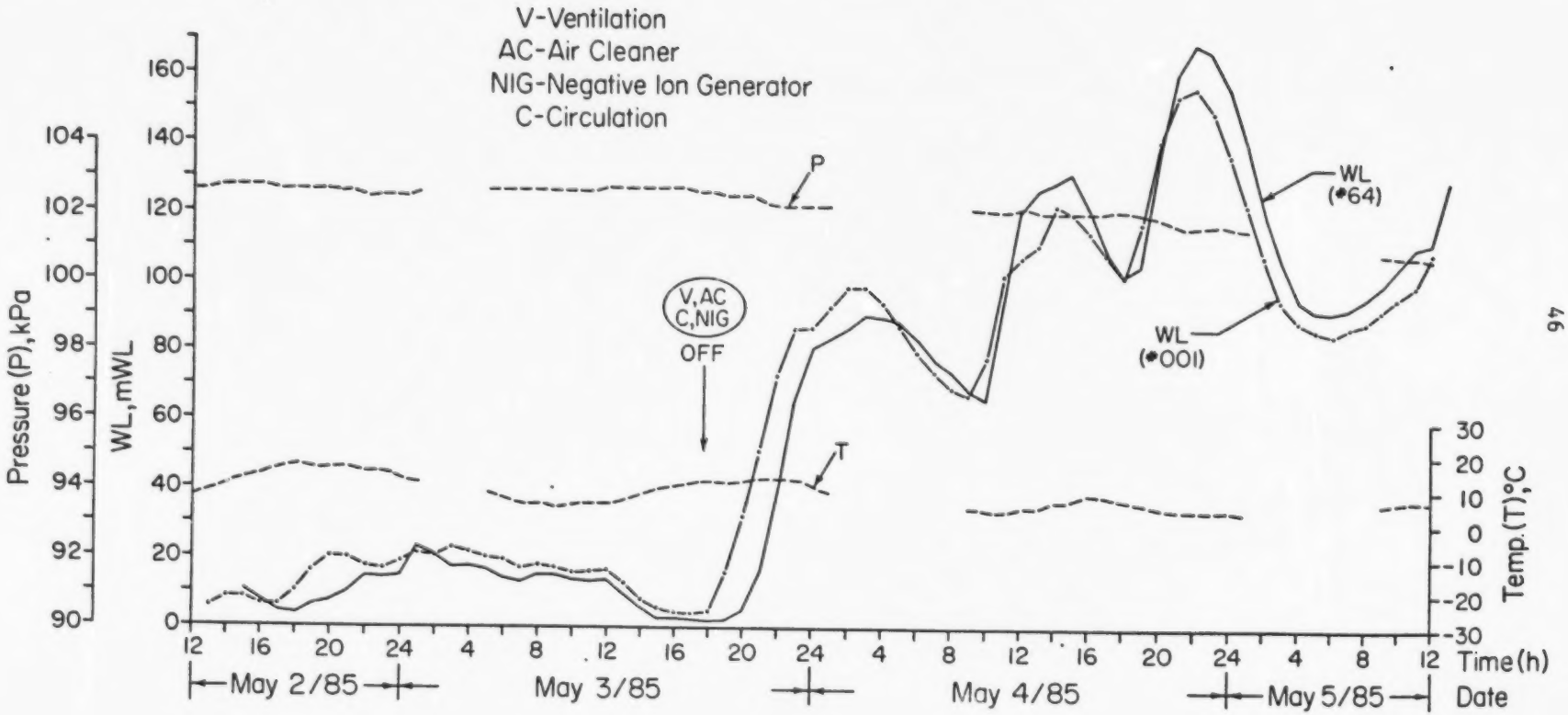

Fig. 16 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. The solid line and broken line for WL refer to the living room and laundry room, respectively.

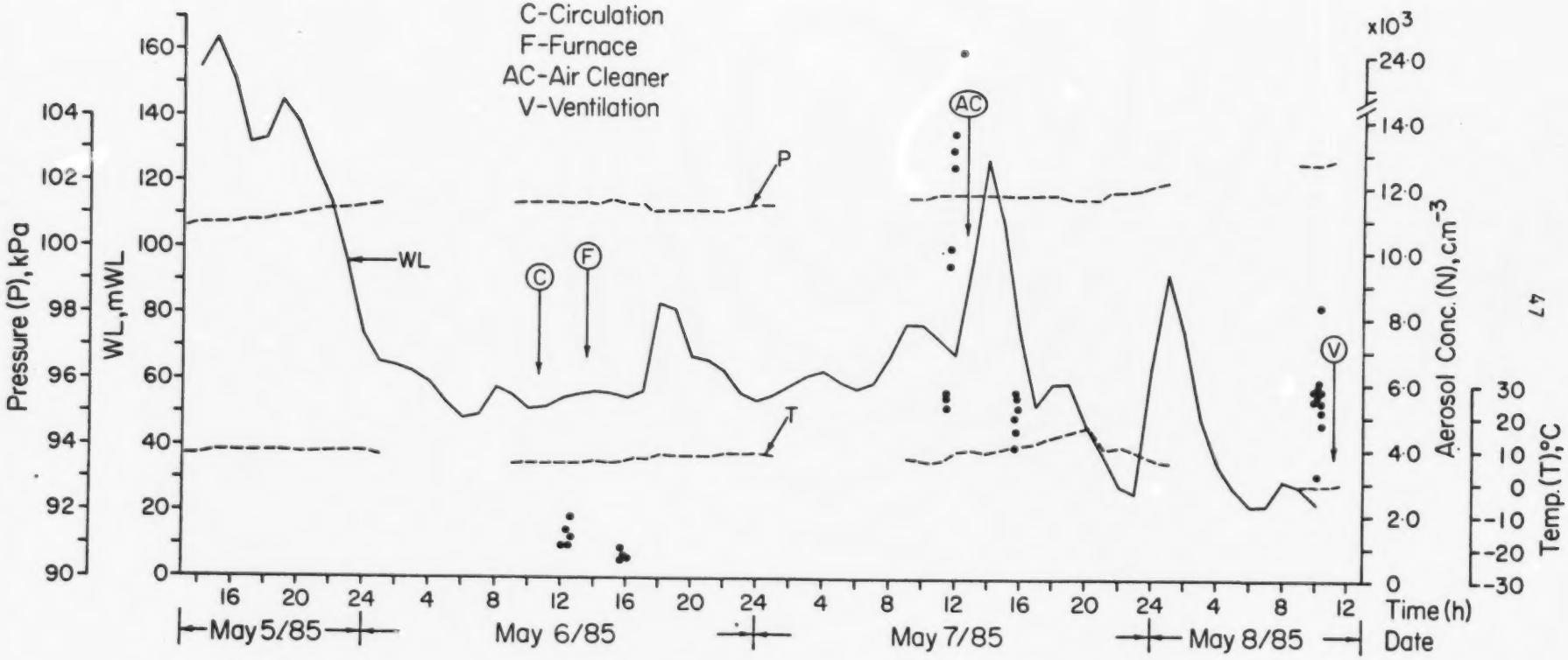

Fig. 17 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), aerosol concentration (·), and control operations, indicated by vertical arrows. Data taken in the living room.

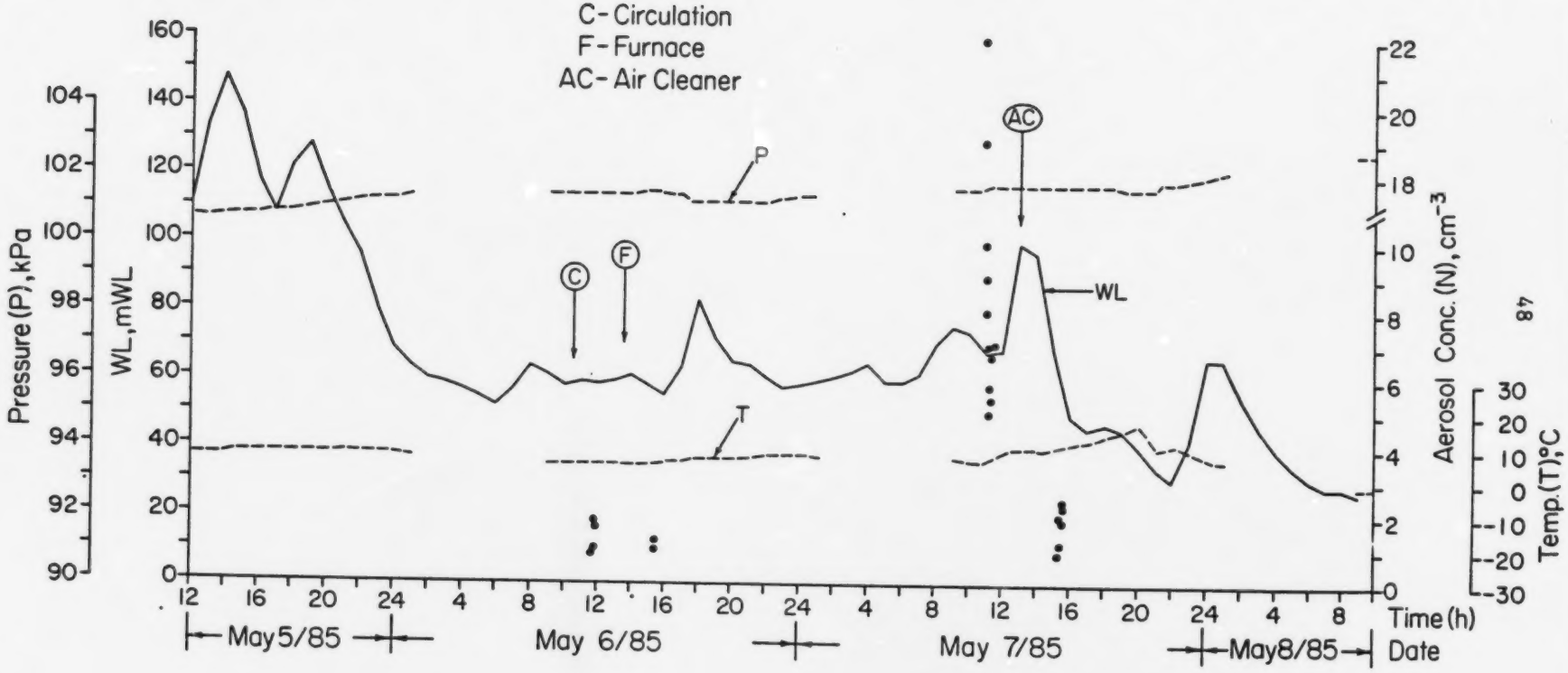

Fig. 18 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), aerosol concentration (·), and control operations, indicated by vertical arrows. Data taken in the laundry room.

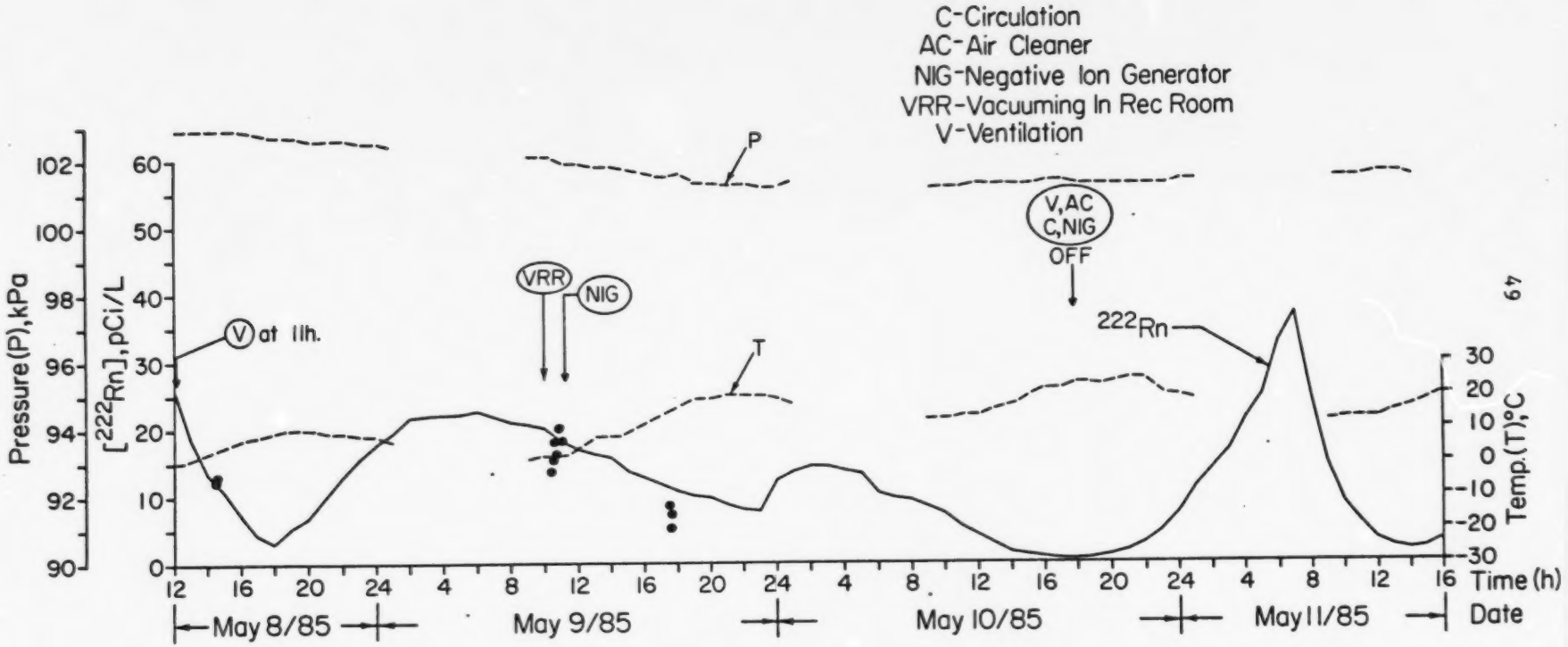

Fig. 19 - Radon gas concentration versus time. Also shown are the outdoors temperature (T), pressure (P), aerosol concentration (·), and control operations, indicated by vertical arrows. Data taken in the living room.

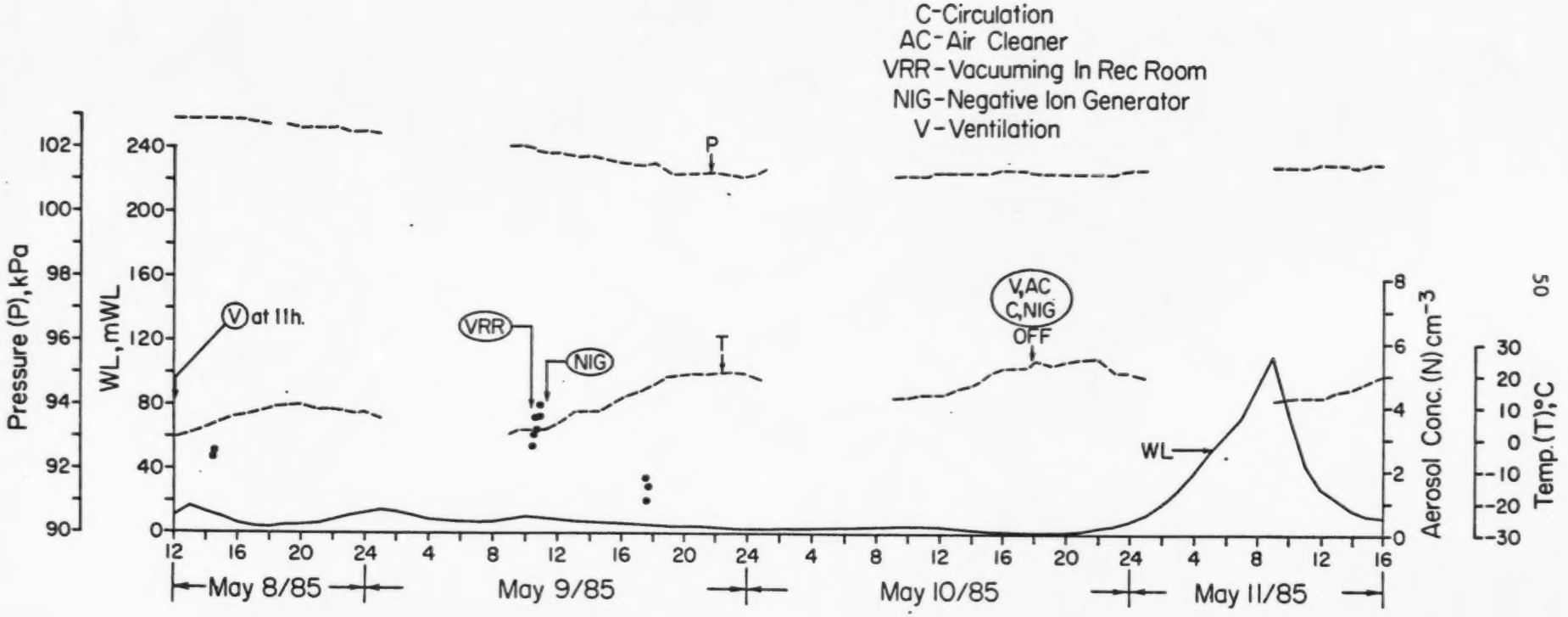

Fig. 20 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), aerosol concentration (·), and control operations, indicated by vertical arrows. Data taken in the living room.

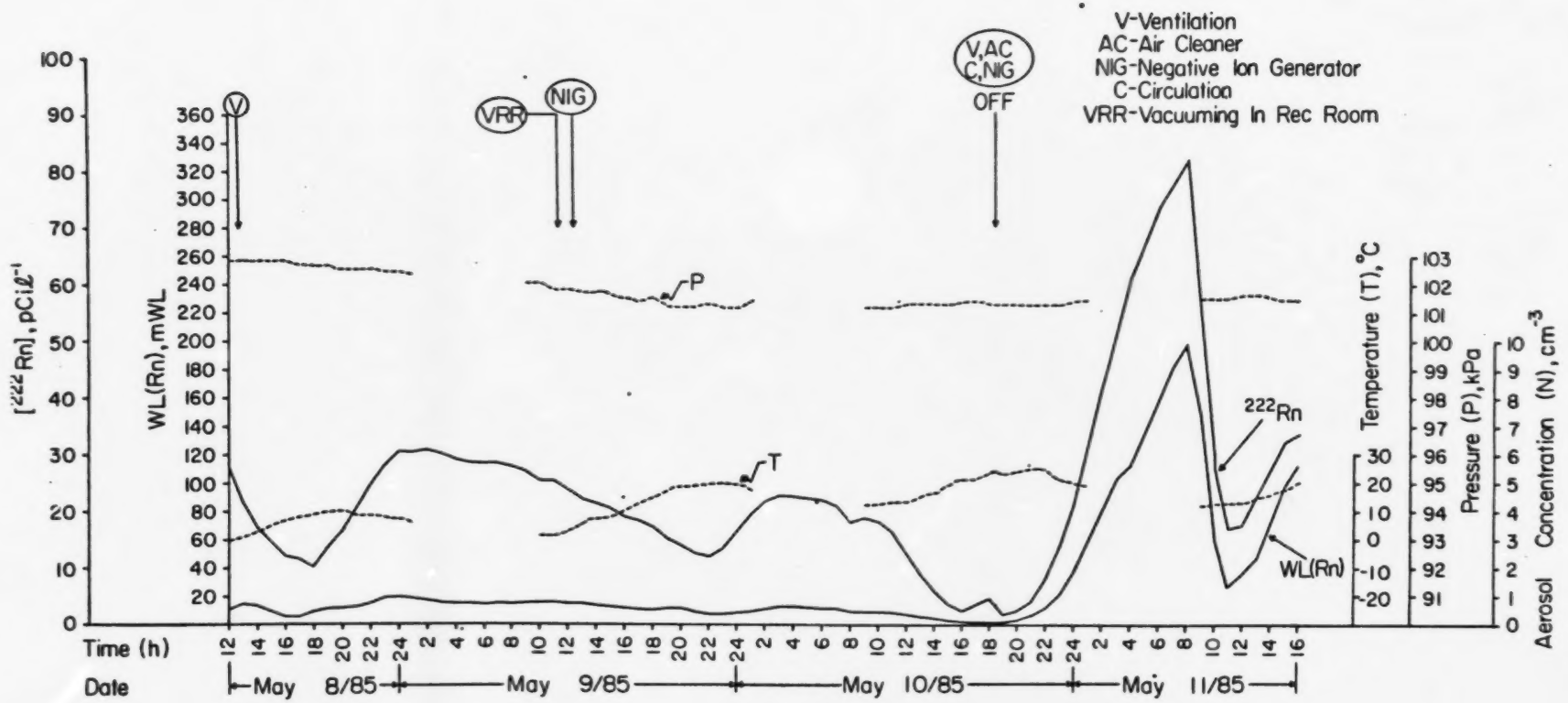

Fig. 21 - Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the laundry room.

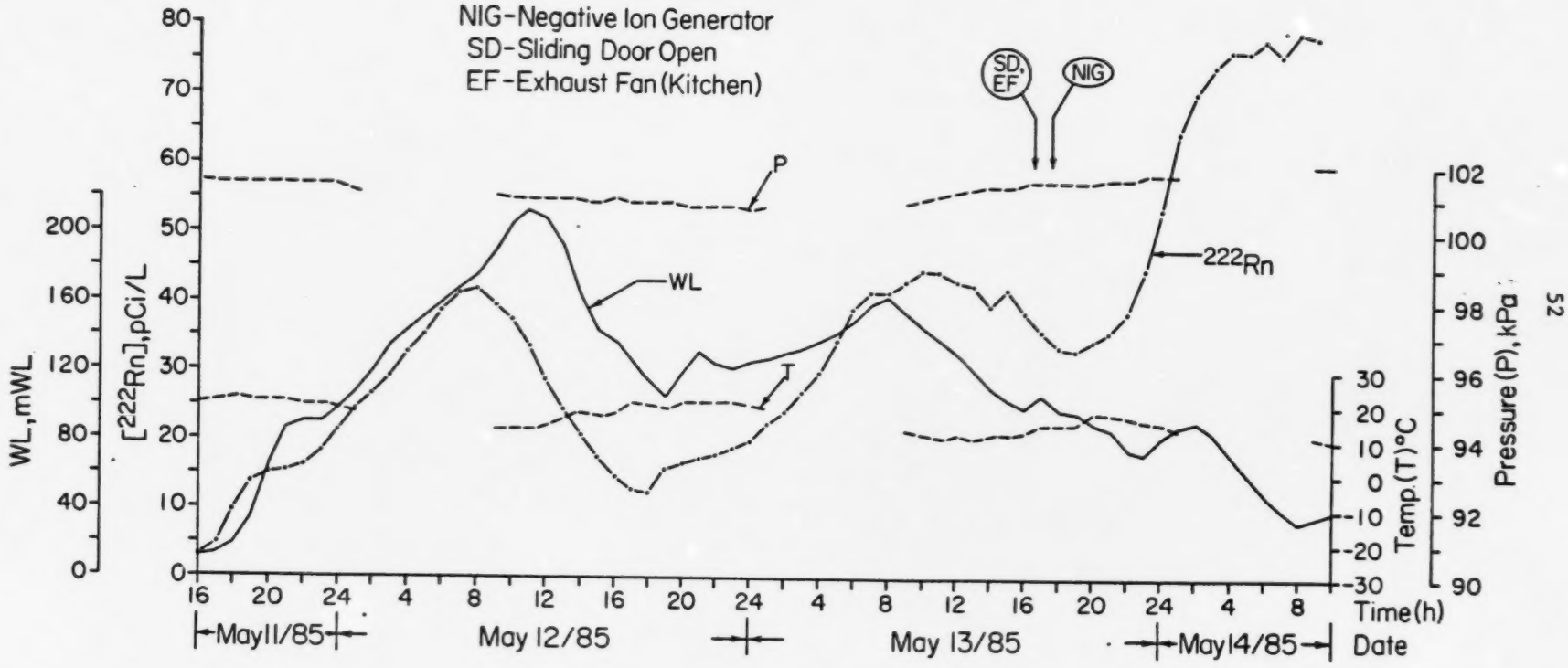

Fig. 22 - Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the living room.

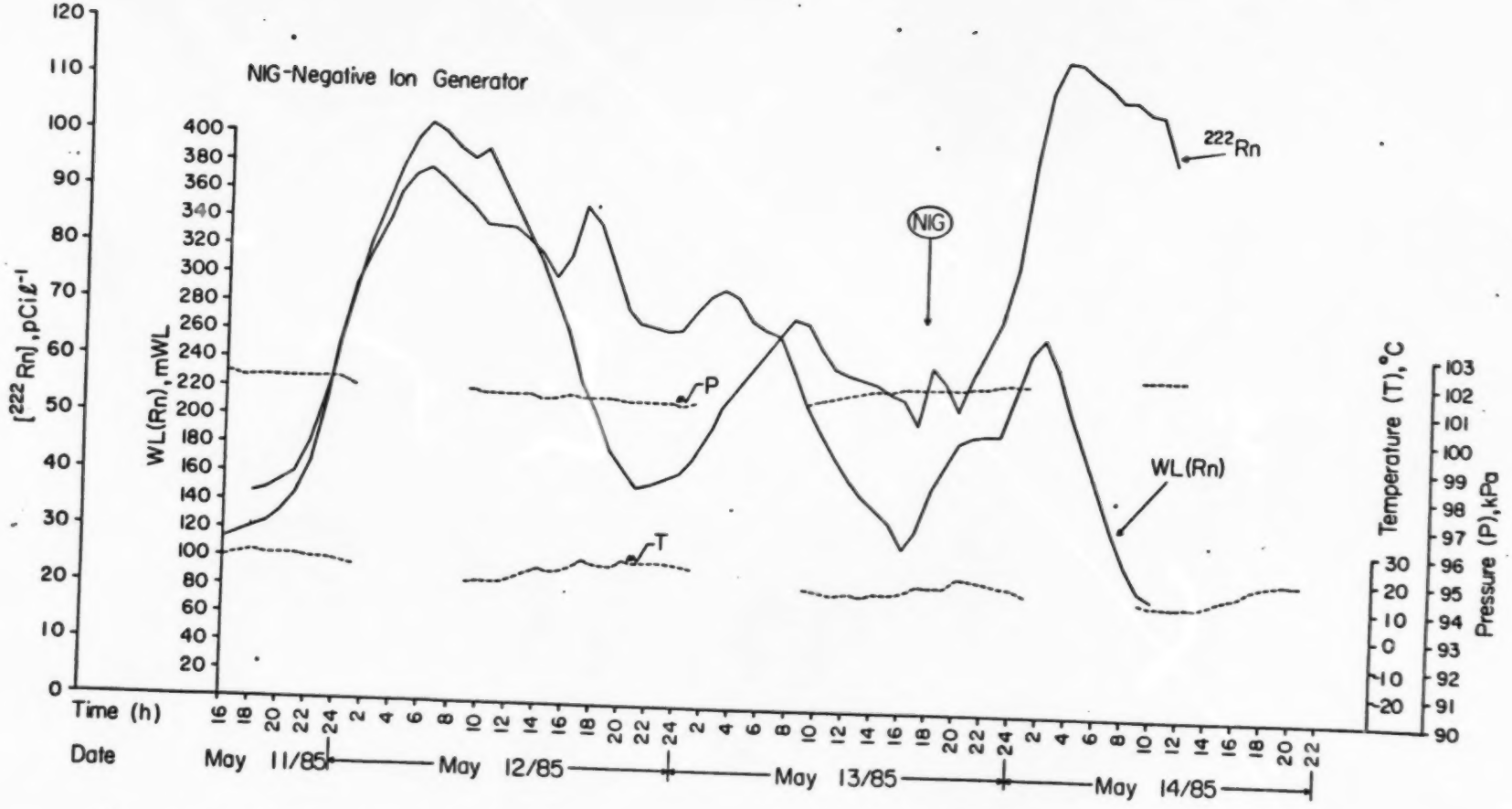

Fig. 23 - Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the laundry room.

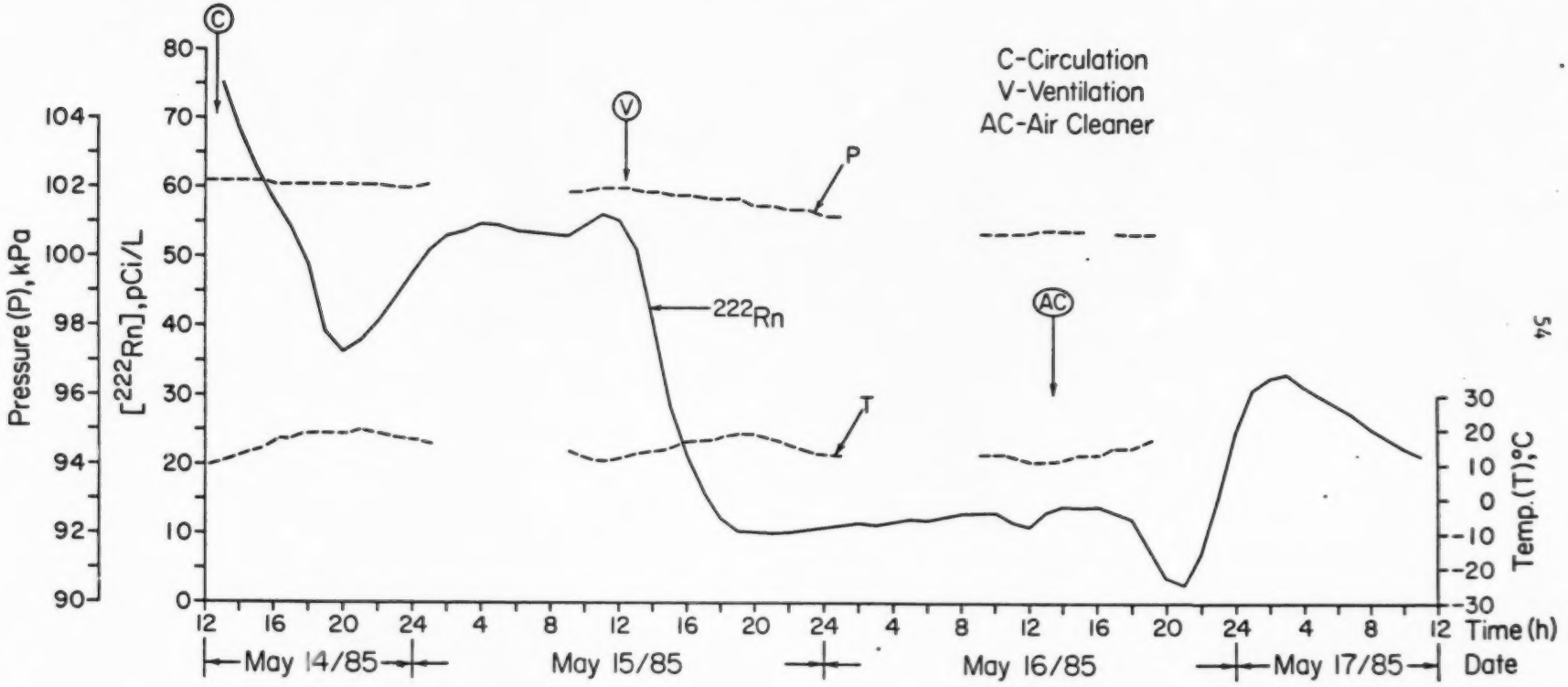

Fig. 24 - Radon gas concentration versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the living room.

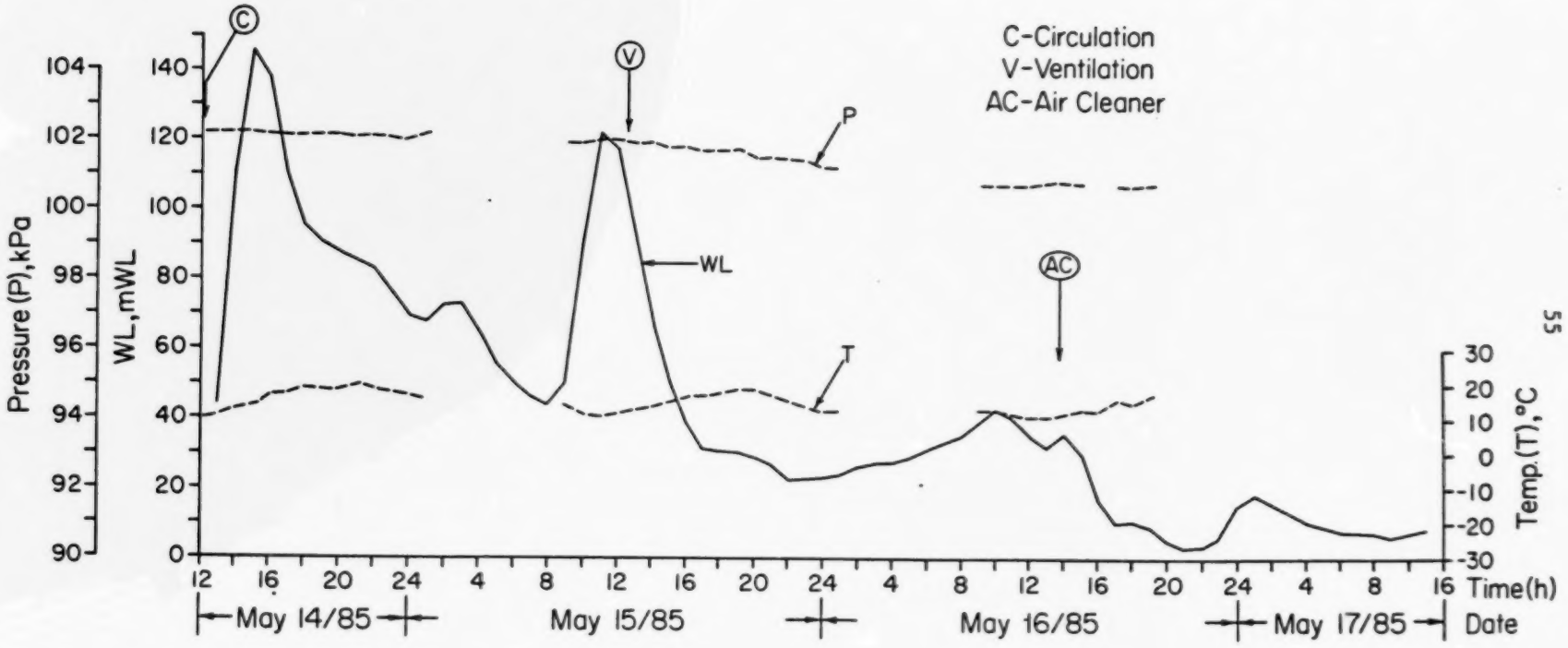

Fig. 25 - Radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the living room.

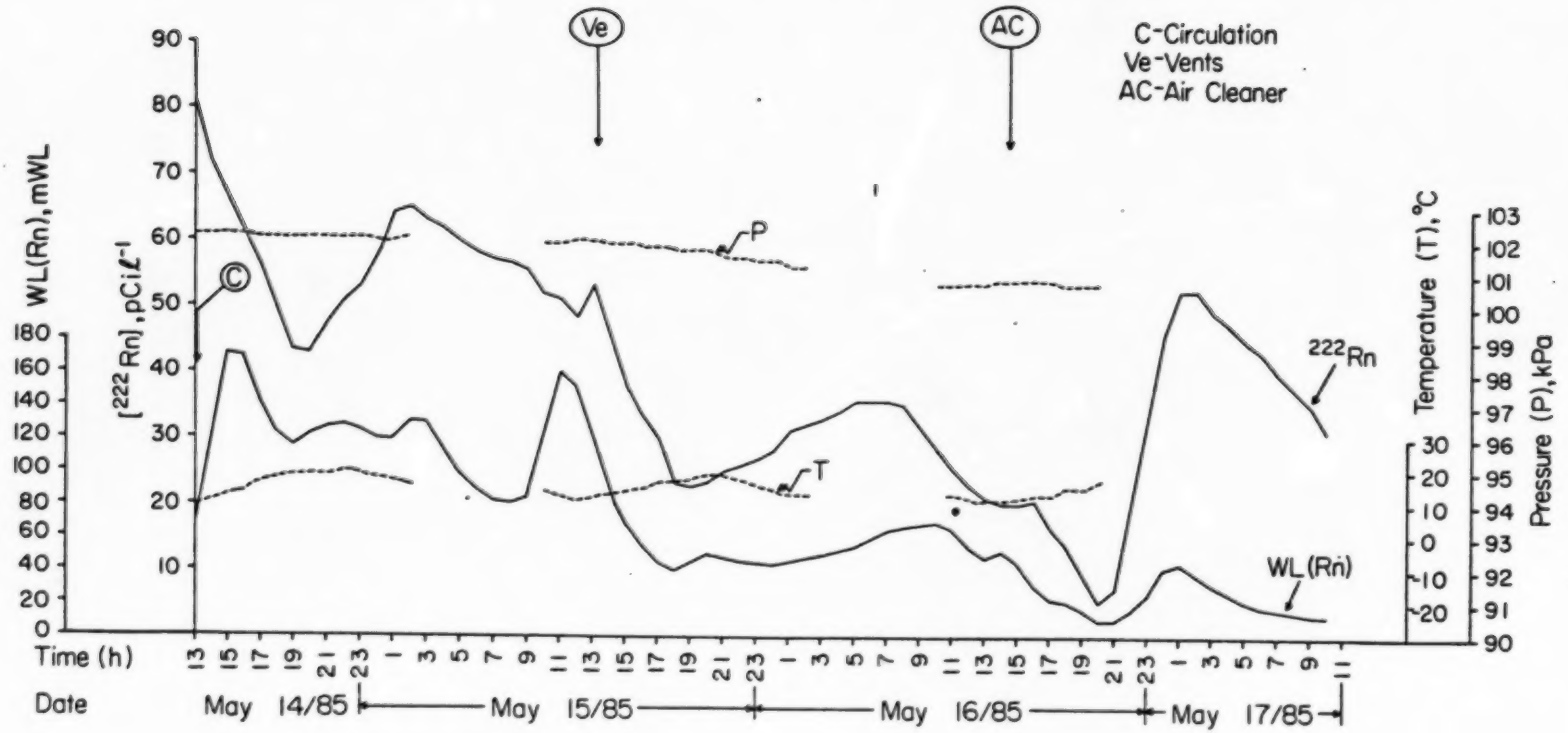

Fig. 26 - Radon gas concentration and radon daughter Working Level versus time. Also shown are the outdoors temperature (T), pressure (P), and control operations, indicated by vertical arrows. Data taken in the laundry room.

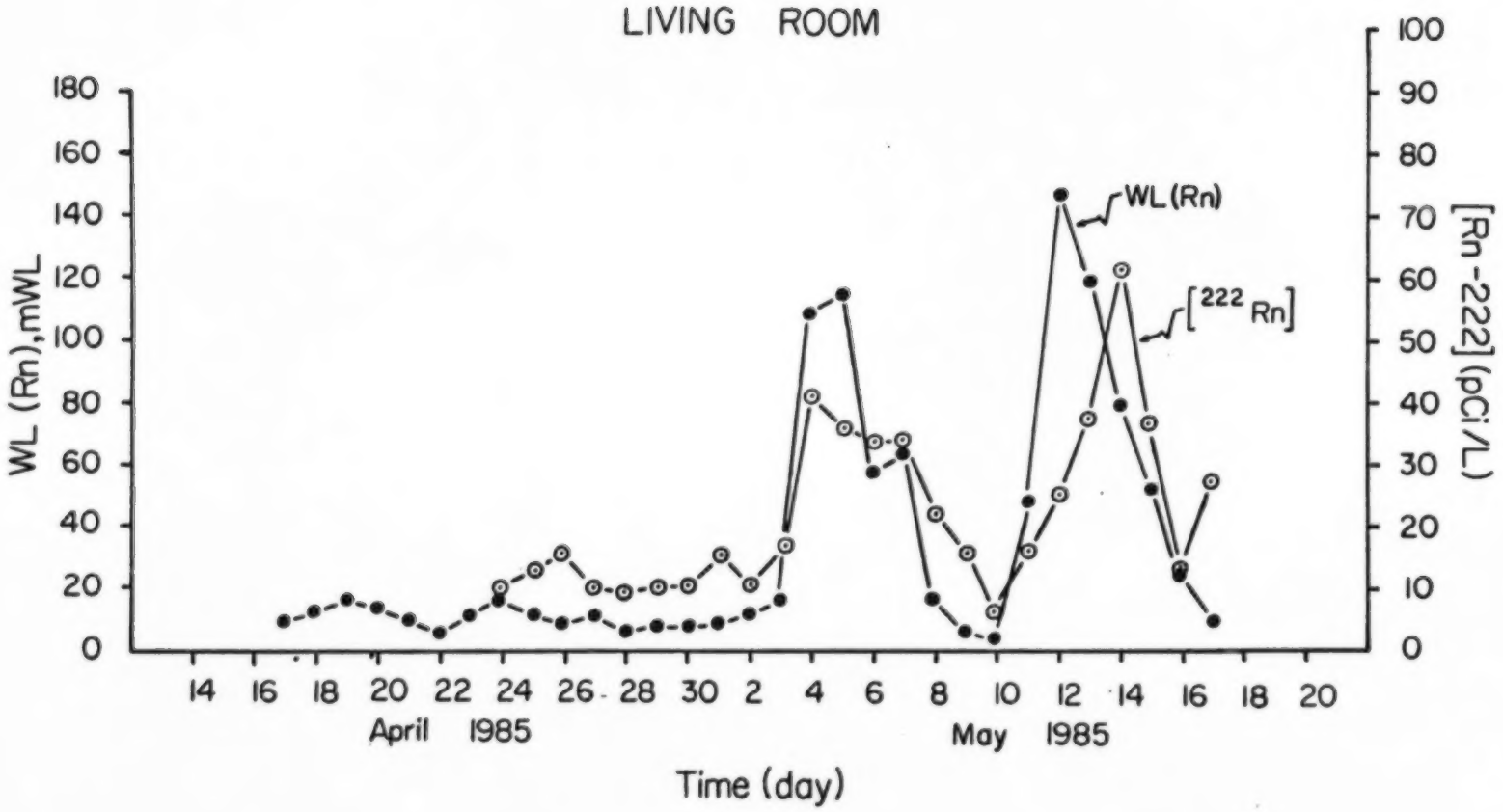

Fig. 27 - Radon gas concentration and radon daughter Working Level (daily average values) versus time.

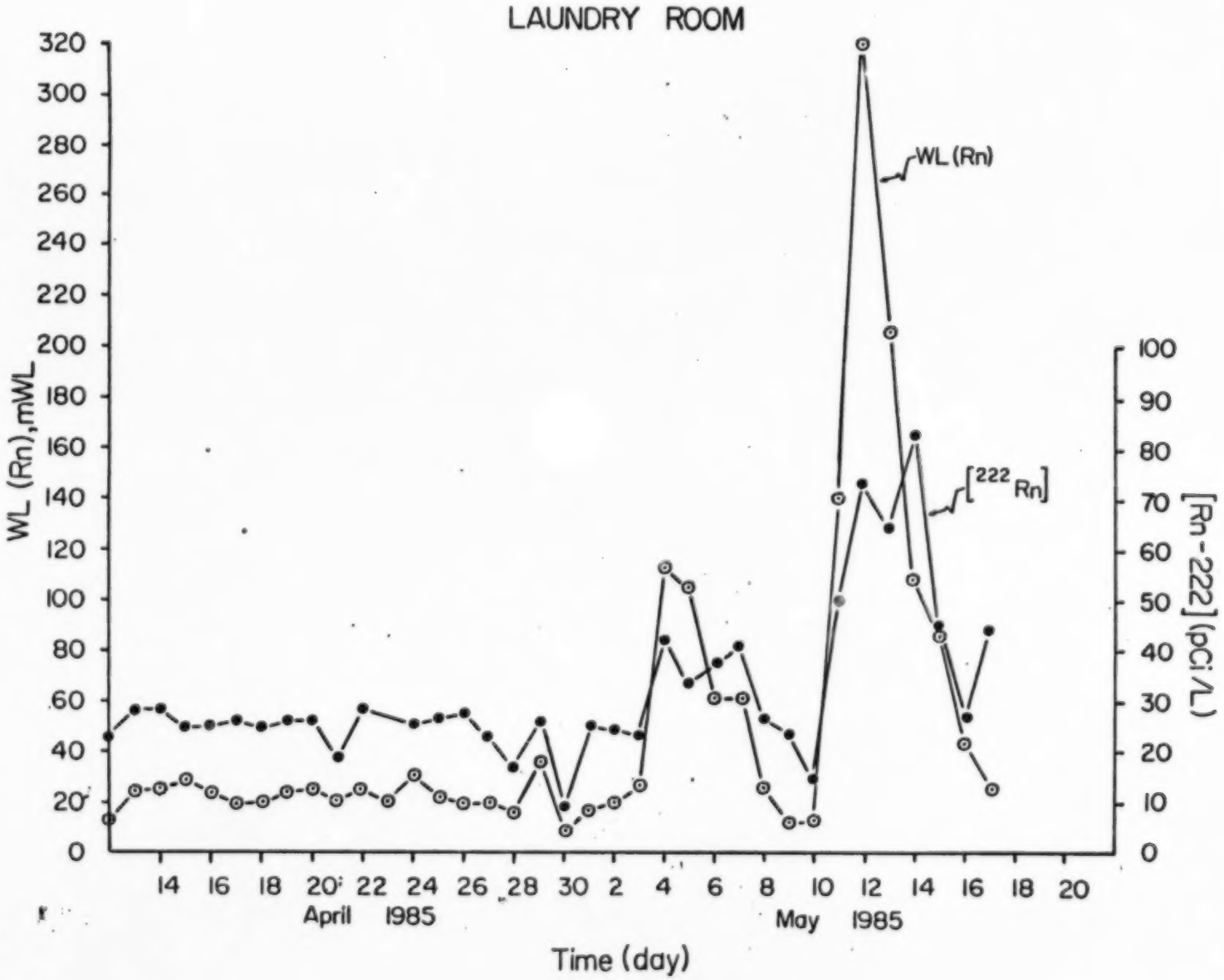

Fig. 28 - Radon gas concentration and radon daughter Working Level (daily average values) versus time.

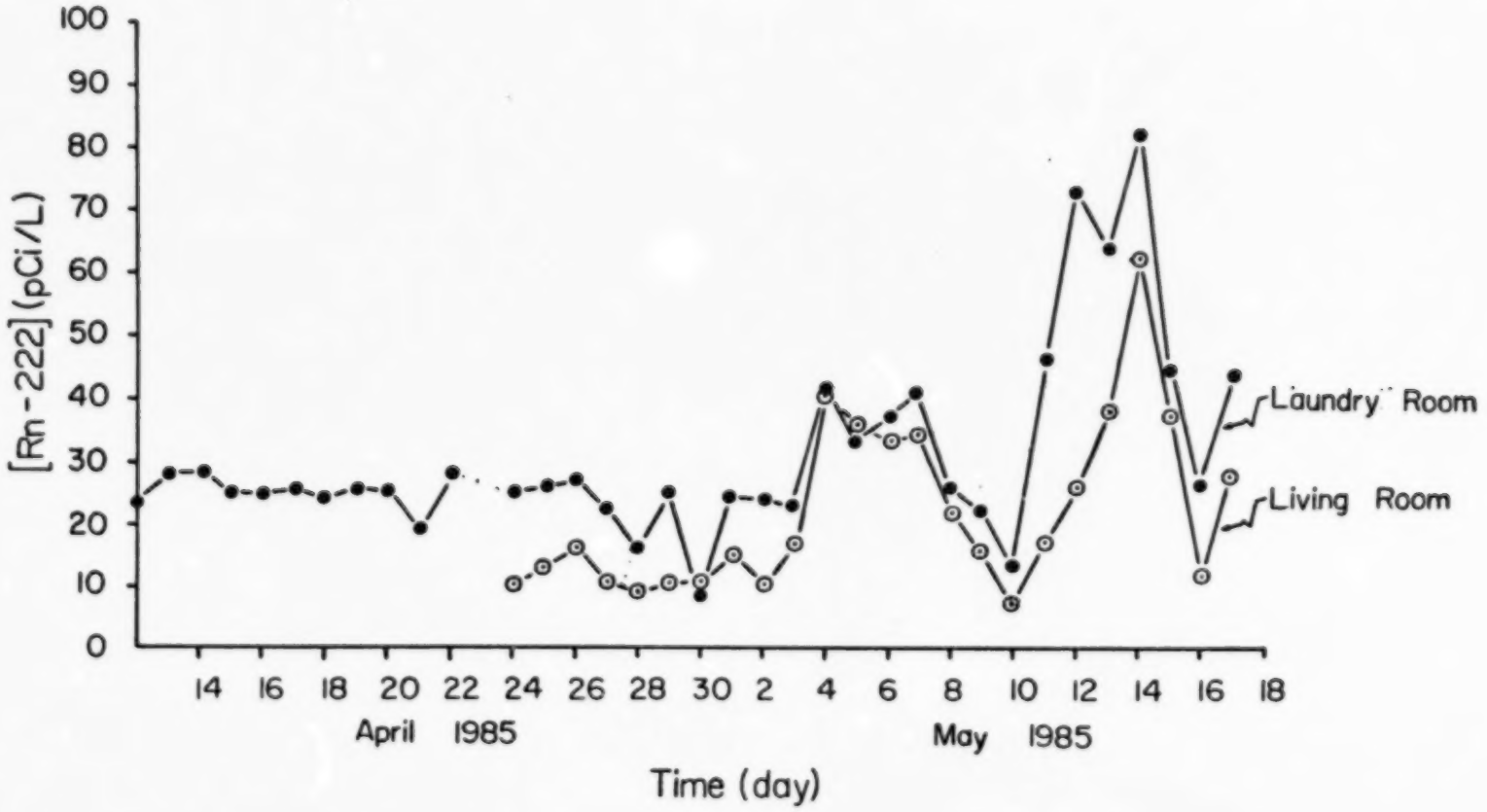

Fig. 29 - Radon gas concentration (daily average values) versus time.

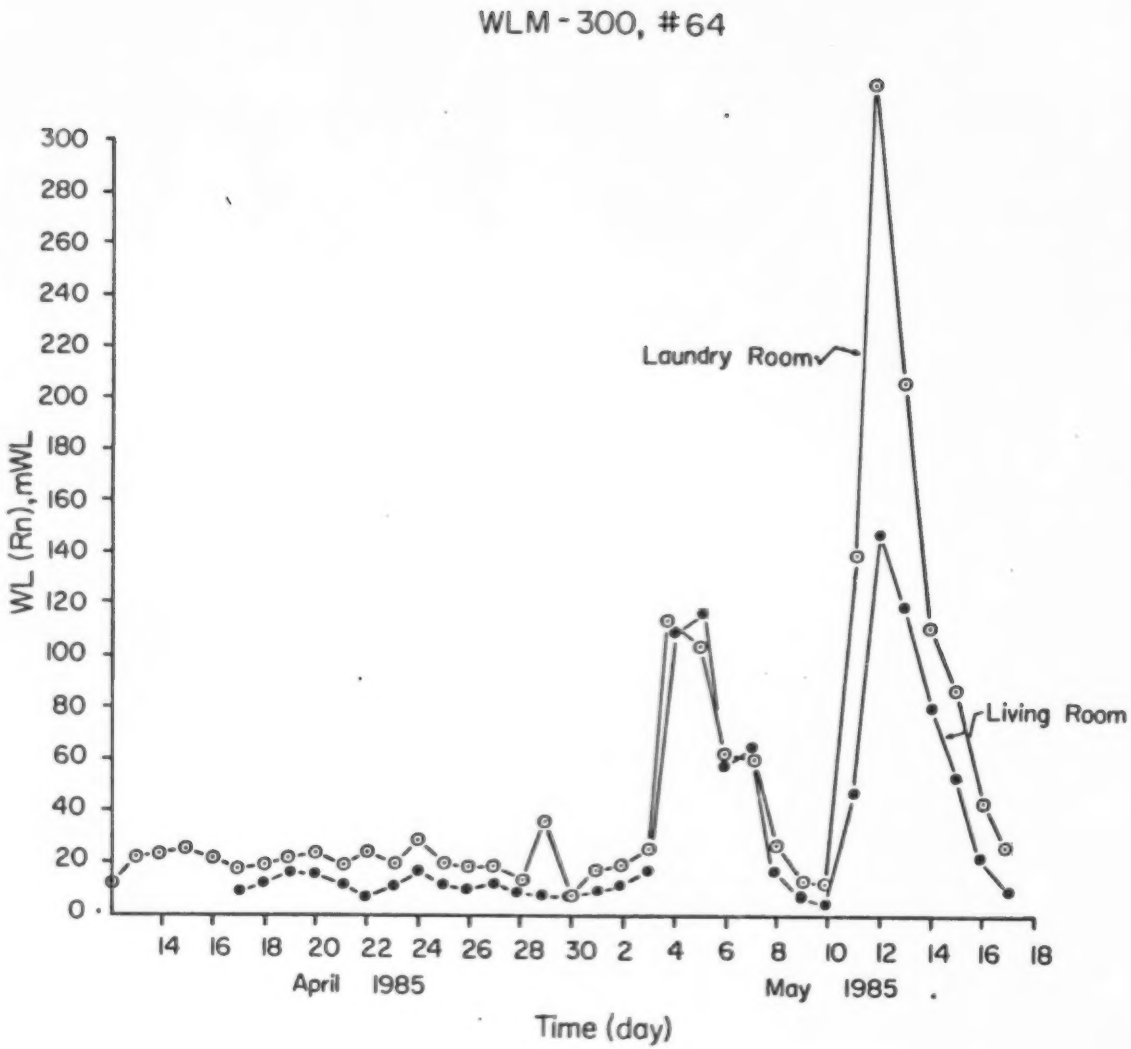

Fig. 30 - Radon daughter Working Level (daily average values) versus time.